AQUACULTURE FEED
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TOWARD RESILIENT AQUACULTURE IN AFRICA: INNOVATIVE AND SUSTAINABLE AQUAFEEDS THROUGH ALTERNATIVE PROTEIN SOURCES

HOW TO BALANCE SUSTAINABILITY AND PALATABILITY OF AQUACULTURE FEEDS IN AFRICA

ENZYME SUPPLEMENTATION (PHYTASE AND XYLANASE) IMPROVES LOW QUALITY DIETS IN NILE TILAPIA

MECHANISMS, CHALLENGES AND OPPORTUNITIES OF AQUAFEED EXTRUSION

AQUACULTURE FEED
MAGAZINE AFRICA

The African Aquaculture Feed Magazine is an essential tool for the development of aquaculture feed management in the region. Indeed, the magazine offers a valuable and up-to-date source of information on the latest advances in aquaculture feed, new market trends, best management practices and technical recommendations for improving aquaculture production.
By providing feature articles, case studies, market analyses and interviews with industry experts, Africa's aquaculture feed magazine enables aquaculture professionals to stay informed and up to date with the latest innovations in fish and shellfish feed. This enables them to adapt their practices in a more sustainable and efficient way, taking into account the environmental, economic and social issues linked to aquaculture production.
In addition, the Africa Aquaculture Feed Magazine also helps to promote good feeding practices in aquaculture, highlighting innovative initiatives and projects that are having a positive impact on the sustainability of aquaculture production in the region. By fostering the sharing of knowledge and experience between industry players, the magazine plays an essential role in building the capacity of aquaculture professionals and in the continuous improvement of aquaculture feed management practices in Africa.
The Africa Aquaculture Feed Magazine is a contributing tool for the development of aquaculture feed management in the region, informing, raising awareness and inspiring industry players to adopt more sustainable practices and contribute to the growth and prosperity of aquaculture in Africa.

LIST OF THE EDITORIAL TEAM OF THE AFRICA AQUACULTURE FOOD MAGAZINE

EDITORIAL

DEAR READERS

Aquaculture is fast emerging as a vital sector for food security and economic development in Africa. As the continent faces the challenges of population growth and dwindling wild fish stocks, the need for sustainable and efficient aquaculture practices has never been more pressing.

Aquaculture nutrition research has evolved considerably over the last few decades, stimulated by the growth of aquaculture as an important food source, now recognised as the main alternative to meet the needs of a growing African population, increasingly aware of the quality and importance of fish in the diet for a longer and healthier life. At the heart of this effort is the quality of aquatic feed, which plays a crucial role in the health, growth and overall productivity of farmed fish. This issue of the magazine explores the importance of feed quality in promoting a thriving aquaculture industry in Africa, as it directly influences the growth rates and health of aquatic species and the success of aquaculture production. Poor quality feed, on the other hand, can lead to stunted growth, increased susceptibility to disease and higher mortality rates.

On a continent where aquaculture is seen as a solution to food insecurity, the consequences of poor quality feed can be detrimental and undermine the very objectives of the sector. So optimising fish nutrition is not just a technical challenge, but a strategy for profitability and sustainability. Furthermore, the economic viability of aquaculture operations is closely linked to feed quality, which not only boosts profitability but also contributes to the sustainability of aquaculture practices by reducing waste and minimising environmental impact. On the other hand, the use of poor quality feed can increase operating costs and reduce profits, discouraging investment in the sector, so the development of a robust aquatic feed industry in Africa is essential to develop local economies and socials.

Furthermore, the importance of feed quality goes beyond economic and social considerations; it also encompasses environmental sustainability. The aquaculture sector must strive to minimise its ecological footprint, and this starts with feed.

By investing in research and development to improve feed formulations and manufacturing process, Africa can pave the way for sustainable aquaculture practices.

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TOWARD RESILIENT AQUACULTURE IN AFRICA: INNOVATIVE AND SUSTAINABLE AQUAFEEDS THROUGH ALTERNATIVE PROTEIN SOURCES

This document explores the challenges and opportunities within the African aquaculture sector, particularly focusing on the need for innovative and sustainable aquafeeds derived from alternative protein sources.

As the demand for aquaculture continues to rise, the reliance on traditional fishmeal presents significant socioeconomic and ecological risks.

This review synthesizes current knowledge on alternative protein sources, identifies challenges in their utilization, and proposes solutions to enhance the sustainability and resilience of aquaculture in Africa.

1. INTRODUCTION

Aquaculture production in Africa is gradually expanding to boost food production, improve quality health nutrition, and achieve food security. In addition, the sector is a significant source of livelihood for over 6.1 million people on the continent, following its various production chain segments. Despite the production volume of 2.5 million tons of seafood, Africa's aquaculture sector must grow by 74% to sustain current per capita consumption through 2050. However, the lack of access to high-quality and affordable feed for farmed species poses a potential barrier to the sector's growth. The production volume is currently estimated to grow by over 20% from 2.3 million tons to 2.8 million tons between 2022 and 2032.

The most commonly produced species in African aquaculture include tilapia, African catfish, and common carp, which usually have 1%–3% fishmeal in their diets. However, other finfish species produced in Africa require higher fishmeal inclusion levels. Assuming an average of just 3% fishmeal in aquaculture diets for African species, 15,000 tons of additional fishmeal will be needed to increase aquaculture production by the previously mentioned 500,000 tons until 2032 (assuming a feed conversion ratio of 1). In 2020, African fishmeal production was estimated to be 420,000 tons, of which over 90% were exported. Including imports, about 80,000 tons of fishmeal were used for aquafeeds in Africa in 2020.

The African fishmeal production equates to about 8% of global production, but only about 1.5% of the global production is used as feed ingredients in Africa. Fishmeal and fishmeal-based aquafeeds produced in Africa or on other continents are usually uneconomical for small-scale fish farmers in African countries.

Trying to elevate African aquaculture production through increased production of wild-caught fishmeal for feed production would further exploit forage fish stocks on the African coast and increase exports due to higher financial margins. Exploiting forage fish from natural ecosystems significantly affects the food web and socioeconomic factors. Over 30% of fish stocks on the African coast are already considered biologically unsustainable, including forage species like Sardinella and bonga used for fishmeal production. An increase in catches of forage fish can, therefore, have detrimental consequences for the ecosystems of African waters. Furthermore, the depletion of fish stocks could have profound implications for the livelihoods of communities dependent on fishing and related industries, as is the case in many African regions.

Fishmeal industries can directly compete with the artisanal fishing and postharvest sectors, threatening the jobs and livelihood of fishers and postharvest workers. Furthermore, feeding forage fish to farmed fish in protein-starved Africa is socially questionable. Therefore, African aquaculture must rely on fishmeal alternatives less suitable for human consumption, like plant-based proteins, animal by-products, insect meals, and microbial biomass or single-cell protein (SCP), to ensure ecological and socially sustainable long-term growth.

Over the years, several feed materials of both animal (insects, animal by-products) and plant (rapeseed, soybean, Bambara seed, peanut, Pigeon pea) origins have been tested for suitability as fish meal substitutes in aquaculture using several African commercial fish species. Despite the availability of these innovative feed sources in Africa, their commercial utilization is limited or not achieved due to the lack of requisite skills and advanced processing technologies to guarantee steady access, improve their nutritional quality, and contamination-free production, driven by the lack of critical infrastructure, policy support, and funding. Assuming a protein content of 70% in fishmeal, at least 10,500 tons of protein has to be derived from new sources for the estimated growth of the African aquaculture industry by 2032.

This comprehensive review, therefore, aims to (i) synthesize the current knowledge regarding the health and nutritional value of alternative protein sources for African aquaculture species, (ii) identify potential benefits of these alternative protein sources for Africa's aquaculture sector and key challenges undermining their commercial utilization, and (iii) suggest practical solutions to harness the potential utilization of these innovative feed sources for sustainable growth of Africa's aquaculture sector. We provide a foundation for informed decision-making in pursuing more sustainable and resilient African aquaculture by critically evaluating alternative protein resources and their implications.

2. CURRENT STATE OF AFRICAN AQUACULTURE AND AQUAFEED PRODUCTION

Africa is the fourth biggest aquaculture producer in the world, contributing about 2.5 million tons of seafood and representing 1.9% of global aquaculture production in 2022 (Fig 1).

Considering African aquaculture production statistics finfish contributed about 91.8%, followed by algae at 7.5%, crustaceans at 0.35%, mollusks at 0.33%, and other aquatic animals at 0.01%.

Africa's inland freshwater aquaculture contributed 91.9% of the total production of aquatic animals, compared to the marine contribution of 8.1%.

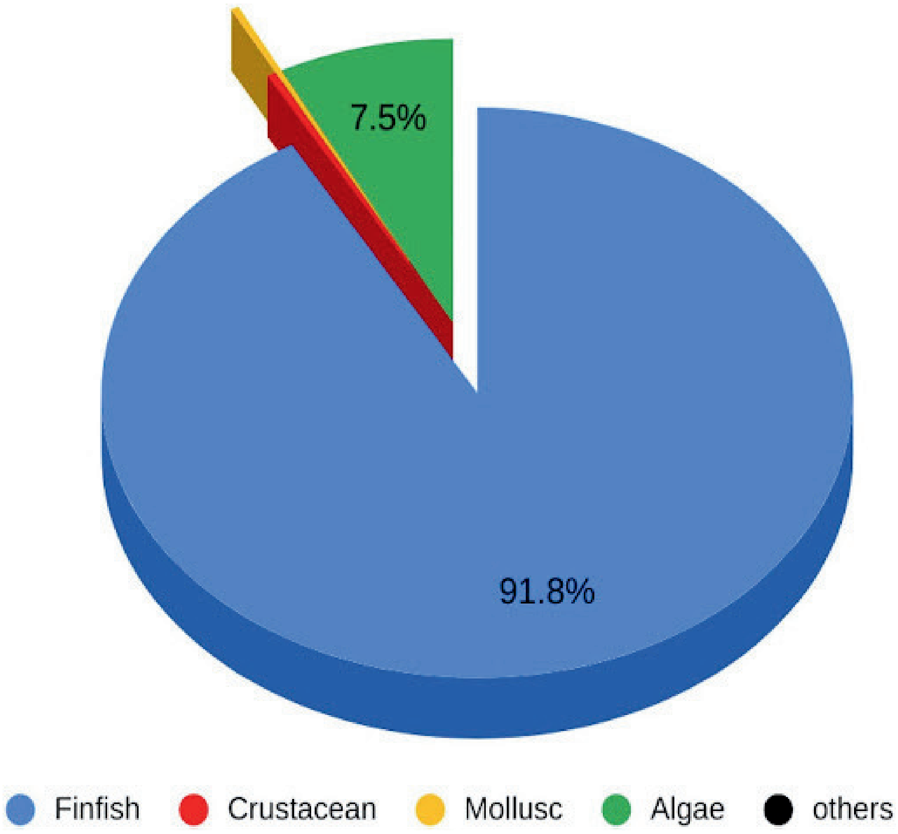


Fig 1 : Relative contribution of aquaculture divisions to total production in Africa.

Based on aquaculture production statistics between 2000 and 2021, Egypt contributed about 65.5% of African production output, making it the region's largest aquaculture producer. Nigeria is the second largest producer (12.6%), followed by Tanzania (7.8%) and Uganda (4.9%).

The continent is known to be one of the largest producers of African catfish species globally.

Other popular commercial finfish species produced in the region include tilapia (Egypt being the third largest producer in the world) and carp species.

African catfish (Clarias gariepinus) production in Africa increased from 65,000 tons to about 200,000 tons between 2006 and 2022, and tilapia aquaculture production grew from 27,000 tons in 1990 to 1,287,053 tons in 2019.

Africa was the fastest-growing continent in aquaculture production between 2000 and 2022 and is estimated to be the second fastest moving forward.
To ensure the sustainable growth of the African aquaculture sector, it is essential to consider feed as a critical production factor. Africa's aquafeed production experienced a 2.38% decline from 1.484 million tons in 2021 to 1.449 million tons in 2022. Due to the low and stagnating production volume and low quality of locally produced aquafeeds, aquaculture production in the continent is currently heavily dependent on imported fish feeds and ingredients from Asia (China, India, Thailand); the Middle East (Israel); and Europe (Germany, Russia, Netherlands, Norway, Denmark). In 2016, an estimated 1,651,146 MT of aquafeeds was imported for tilapia and African catfish production in Egypt and Nigeria. Significant inflation often affects these imports, posing a severe challenge to African aquaculture development.

The inflation is blamed on global economic meltdowns and conflicts, particularly in parts of the Middle East and Europe, which induce scarcity and price volatility of feeds and feed ingredients. For instance, imported fish feed in Ghana is heavily impacted by import duties, taxes, and transportation, accounting for about 80% of the total cost. Nigeria faces a comparable situation, with approximately 95% of aquafeeds being imported and over 70% of the feed cost allocated to taxes, import duties, and transportation. A survey report revealed that over 84% of fish farmers in the Benin Republic rely on imported fish feeds and ingredients for fish production. Concerns have been raised that 85% of fish production costs in Egypt are attributed to feed expenses, mainly due to high importation costs and reliance on foreign feed ingredients. Similarly, Uganda's aquaculture industry relies on imported feed from Europe due to insufficient local fish feed producers, weak investment incentives, and government policy negligence.

3. NUTRITIONAL ASPECTS OF POTENTIAL ALTERNATIVE PROTEIN SOURCES FOR AFRICAN AQUAFEEDS

3.1 PLANT-BASED PROTEINS

Plant proteins are abundant, cost-effective, and nutritionally adequate for various fish species. Key nutritional factors for fishmeal alternatives include low carbohydrate content, high protein levels, a suitable amino acid profile, and good digestibility. Promising plant protein sources produced in Africa include pea, rapeseed, sesame, soy, sorghum, and sunflower.

- **Soy Protein:** Widely used and studied, soy protein effectively replaces fishmeal in diets for tilapia, carp, and African catfish, demonstrating good growth performance and nutrient utilization.

- **Sesame Proteins:** Derived from oil extraction, sesame proteins have high protein content but lack certain amino acids. They have been successfully included in diets for tilapia and carp without negatively impacting growth.

- **Sunflower Proteins:** Adaptable to various climates, sunflower proteins can partially replace fishmeal, although their high fiber content limits inclusion levels.

- **Rapeseed Proteins:** With a balanced amino acid profile, rapeseed proteins show promise as fishmeal substitutes, although anti-nutritive factors can impair fish growth. Processing can enhance their nutritional value.

- **Pea Proteins**: Investigated for their potential as fishmeal alternatives, pea proteins face challenges due to fiber and anti-nutritive factors, restricting their dietary inclusion.

- **Sorghum**: While abundant and drought-resistant, sorghum has low protein content and lacks essential amino acids, necessitating further research to evaluate its potential in aquafeeds.

3.2 ANIMAL BY-PRODUCTS

Animal by-products are considered excellent alternatives to fishmeal due to their high protein content and palatability, readily available and economically attractive protein sources. Africa produces significant amounts of animal by-products from cattle, poultry, and pigs, which can be utilized in aquafeeds.

- Commonly tested animal by-products include feather meal, poultry by-products, meat and bone meal, blood meal, and fishery by-products. These have been shown to replace fishmeal in tilapia and African catfish diets without adversely affecting growth.

- Lesser-known by-products, such as donkey blood meal and crocodile meal, also present potential for aquafeeds.

- Fishery by-products, including shrimp and fish remnants, can partially replace fishmeal, although high substitution levels may compromise growth performance.

3.3 INSECTS

Insects are gaining recognition as a sustainable protein source for aquafeeds, particularly in Africa, where they have been part of the human diet historically.

The continent boasts a rich diversity of approximately 2300 insect species, with around 644 identified as suitable for human consumption. While various regions in Africa, such as Southern, Central, West, East, and North Africa, are known for their diverse insect populations, reliable data on their production volumes remains scarce. Research indicates that many insects are high in crude protein and can effectively replace fishmeal in aquaculture feeds without negatively impacting fish health or growth.

Notably, the black soldier fly (BSF) has shown promise in this regard, with successful production in East Africa yielding an estimated 9780 MT of dried protein annually, potentially meeting 15% of the crude protein demand for fish feed. The economic viability of BSF production also suggests a significant global market potential as the demand for animal feed continues to grow.

3.4 MICROBIAL-BASED FEED INGREDIENTS

Microbial protein biomass, or single-cell protein (SCP), is harvested from microorganisms such as bacteria, fungi, and microalgae. These microorganisms are cultivated on various substrates, primarily agro-waste (like straw, corn stover, sugarcane bagasse, and fruit and vegetable waste) and industrial by-products (including molasses, whey, and spent-brewery products). The cultivation process allows these microorganisms to convert waste materials into protein-rich biomass, positioning the SCP industry as one of the fastest-growing protein producers globally.

In 2021, the global production of SCP was valued at USD 8 billion, with expectations to rise to USD 18 billion by 2030, reflecting an annual growth rate of 9%–10%. Research indicates that SCP could replace up to 19% of plant and animal protein by 2050. Africa, with its rich microbial diversity, has identified about 10 countries as hotspots for microbial diversity, including Algeria, Egypt, Nigeria, South Africa, Kenya, Cameroon, Tanzania, Uganda, Ivory Coast, and Tunisia. However, the microbial diversity profiles in many other African countries remain understudied.

Notably, the black soldier fly (BSF) has shown promise in this regard, with successful production in East Africa yielding an estimated 9780 MT of dried protein annually, potentially meeting 15% of the crude protein demand for fish feed. The economic viability of BSF production also suggests a significant global market potential as the demand for animal feed continues to grow. Despite the potential of SCP, its application in African commercial aquaculture is limited, and production data is sparse. The low research output on SCP in Africa compared to other continents has been noted, and while the concept is still in its infancy in the region, commercial application faces challenges related to infrastructure and technical expertise. Therefore, further exploration of microbial protein for aquaculture nutrition is essential.

Microbial proteins present significant opportunities for African aquaculture, particularly given the abundance of underutilized by-products from the agroindustry, which could foster economic circularity and sustainable practices.

Research has shown that substantial amounts of fishmeal can be replaced with microbial-based sources in species such as African catfish and Tilapia without negatively impacting growth performance.

For instance, substituting fishmeal with bacterial protein (BP) improved the growth of African catfish (C. gariepinus) in a 56-day feeding trial, with no adverse effects on blood, intestinal histoarchitecture, or hepatic enzymatic functions.

Additionally, studies have reported enhanced feed and nutrient utilization in Tilapia (Oreochromis niloticus) when fed diets containing dry yeast protein.

4. BENEFITS AND CHALLENGES OF ALTERNATIVE PROTEIN SOURCES FOR AFRICAN AQUACULTURE

4.1 ECONOMIC VIABILITY

Several fishmeal alternatives that are ecologically sustainable and potentially more affordable than traditional fishmeal derived from overexploited forage fish. A significant portion of fishmeal produced in Africa is exported, leading to low affordability for local aquaculture. Even if local production increased, financial challenges would persist, limiting the sustainability of wild-caught fishmeal.

Plant proteins, particularly soybeans, are highlighted as more affordable alternatives. In 2022, soybeans were produced at a lower cost in Africa compared to the global fishmeal price of 1550 USD/t. While rapeseed is cheaper than soy, its lower protein content results in higher costs per ton of protein. Sunflower seeds are also cheaper than fishmeal, but their protein content is lower than that of soy. Other crops like green peas and sorghum present varying production costs and protein contents, with green peas being particularly cost-effective. The document notes that targeted investments in oilseed production could yield approximately 1.4 million tons of protein for African aquaculture, sufficient to meet the feed demands of 3.5 million tons of African catfish.

Additionally, animal by-products, which do not compete with human nutrition, could provide significant protein sources, with an estimated 4.2 million tons available from cattle alone.

The total annual production of animal by-products in Africa is around 16 million tons, potentially covering the protein needs for 4-8 million tons of catfish. Furthermore, insect and microbial proteins, particularly from Black Soldier Fly (BSF) larvae, could significantly enhance aquaculture production, with the potential to replace up to 60 million tons of feed annually. Even a small fraction of this potential could meet the protein demands of 7.5 million tons of African catfish.

In conclusion, while there are promising alternatives to fishmeal in Africa, the economic viability of these sources depends on addressing affordability and competition with human nutrition demands.

4.2 AVAILABILITY OF ALTERNATIVE PROTEINS AND SOCIAL CONFLICTS

Alternative proteins are potentially available in Africa. However, their accessibility for commercial aquafeeds has not been optimally harnessed. Besides technological deficiencies, other challenges, including seasonal production, climate, and farmers-herders conflict, affect alternative protein abundance in Africa. The increasing demand for alternative proteins raises concerns regarding their sufficiency, availability, and accessibility for aquaculture. Although the production of alternative proteins (plant-related proteins, edible insects, animal by-products) is on the rise globally, there is a dearth of scientific information regarding their status and production statistics in some African countries.

This is attributed to inadequate cooperation between African states on crop and animal production data, as well as knowledge exchange. The production of most alternative proteins in Africa may not be in doubt; however, their commercial viability, availability, and accessibility could be challenging due to several constraints. The seasonal abundance of some alternative proteins (crops and edible insects) could be attributed to the region's agronomic systems and climatic peculiarities. Advanced technologies for seasonless production and availability face technical and economic challenges.

The region's erratic climate pattern affects crop cultivation and general output.

For instance, the rise in temperature has been reported to suppress the growth period, and crops' evapotranspiration invariably decreases yield. Climate change (temperature increase)-orchestrated heat stress adversely affects crops' quality traits, reducing their yield. Variations in rainfall and elevated temperature negatively affect the development and growth of crops.
Insecurity in some parts of the continent has impacted the production and availability of plant-based protein. Conflicts between crop farmers and herders have been a severe challenge for agriculture and agronomic practices in some parts of the West (Nigeria, Chad, Burkina Faso, Mali) and Central African (Central African Republic) countries for decades. The intensification of this conflict has limited the frequent cultivation of the most essential protein-related crops (legumes, cereals) and deprived the food and aquaculture sectors of their commercial availability for use. A typical scenario is the criminal bandit activities in northern Nigeria, which has affected agronomic activities and plunged the production of some protein-related cash crops to abysmal levels. Crop farmers are denied access to their farms due to bandit activities, as their farms are often used as hideouts. The production and use of SCPs are limited to some countries. This could be blamed on challenges such as a lack of technology, culture technique, and skilled personnel. For example, Spirulina was grown in Lake Chad many years ago as a food source to compensate for the local people's protein shortfall. However, algal production for diverse uses is barely successful due to technological challenges.
This document explores the economic viability, availability, and sustainability of alternative protein sources for aquaculture in Africa. It highlights the potential benefits and challenges associated with the adoption of these protein sources, particularly in the context of the continent's unique socio-economic and environmental landscape. The discussion includes insights into the affordability of various protein sources, the impact of social conflicts on availability, and the need for sustainable practices in aquaculture.

4.3 SUSTAINABILITY

It is crucial to shift the choice of protein production toward more sustainable options to prevent further environmental and climate change damage. Emissions from aquaculture are highly dependent on the feed source.

Terrestrial-based animal proteins produce significantly higher greenhouse gas (GHG) emissions than fishmeal and most fishmeal alternatives.

The GHG emissions caused by meat protein (beef, pork, and poultry) are considerably higher than those from fishmeal, emphasizing the need for a transition to more sustainable protein sources in aquaculture.

4.4 FEED SECURITY AND SAFETY CONCERNS

The quality and nutritional status of diets invariably influence farmed animals' growth and meat quality. Although fishmeal suits the nutrient requirements demanded by commercially farmed species in Africa, the large volume of fishmeal used in aquaculture feed is derived from wild-caught fish.

Unfortunately, this fishmeal can be contaminated with toxic materials from both point and non-point sources, such as heavy metals, polychlorinated biphenyls, polycyclic aromatic hydrocarbons, and microplastics/nanoplastics. This contamination presents a significant challenge for aquaculture.

While feasible decontamination methods are available, implementing these solutions significantly increases the production costs of aquafeeds.

These toxicants can bioaccumulate in fish systems and elicit toxic effects such as oxidative distress, neurotoxicity, metabolic disorders, carcinogenicity, genotoxicity, hematological disorder, histopathology, suppressed growth performance, and undermine the health of farmed fish in general. Finding a balance between ensuring safe feed and maintaining economic sustainability is an ongoing challenge for the industry. Switching to fishmeal alternatives could potentially reduce the risk of aquafeed contamination from various harmful substances.

However, it is important to consider that plant proteins are also susceptible to contaminants like pesticides, herbicides, mycotoxins, and heavy metals. These risks often arise from standard farming practices, including inorganic fertilizers and pesticides.

Further, traces of pathogenic bacteria, dioxins, pharmaceuticals, and marker dyes have been reported in some novel animal-by- product-Based proteins utilized for aquafeeds. However, this issue mainly affects subsistent and small-scale aquaculture farms, including local aquafeed producers, and could be attributed to poor processing and storage methods.

Gaps in food safety knowledge related to alternative protein products occur mainly because most research focuses on optimizing production means and possibilities. The African aquafeed industry underutilizes some alternative proteins due to challenges of autogenic (allergens) and exogenous (heavy metals, pesticides, xenobiotics, pathogens) contaminations, which can hinder their nutritional functions and promote toxic situations.

4.5 ANTI-NUTRIENTS

The presence of anti-nutrients in alternative proteins has sparked debates regarding their suitability for aquaculture feed. Chitin, a polysaccharide found in insect exoskeletons, crustacean shells, and fungal cell walls, is recognized for its beneficial properties, such as antimicrobial effects and nutrient stimulation. However, it can also act as an anti-nutrient, negatively affecting fish growth and nutrient digestibility, as evidenced by studies on rainbow trout, turbot, and common carp.

Current processing methods for chitin and other alternative proteins in Africa are often outdated and inefficient, leading to challenges in hygienic processing. Conventional methods like supercritical CO_2 extraction and enzymatic hydrolysis are not widely adopted, exacerbating the issue. Furthermore, insects, while a sustainable protein source, can retain harmful anti-nutrients from plants, including glucosinolates and phytates, which pose risks to fish health.

Alternative plant proteins also contain various anti-nutritional substances, such as saponins, tannins, and protease inhibitors, which hinder nutrient absorption. For example, tannins can bind to enzymes and proteins, reducing digestibility, while phytates limit phosphorus availability in non-ruminant animals. Processing methods like grinding, fermentation, and heat treatment can mitigate these adverse effects, although they may increase production costs.

Animal by-products, including fishery by-products and shrimp meal, can also contain anti-nutritive substances, necessitating careful processing to reduce ash content and improve nutritional quality. Overall, addressing the challenges posed by anti-nutrients is crucial for enhancing the efficacy of alternative proteins in aquaculture.

4.6 SHORTFALL IN PROCESSING INFRASTRUCTURE

Africa's aquaculture is hindered by outdated processing technologies, preventing the region from fully leveraging abundant feed resources, including animal by-products as alternatives to fishmeal. Current processing methods raise hygienic concerns, jeopardizing animal health and increasing disease risks.

Additionally, many alternative proteins contain toxins that require advanced processing techniques for safe incorporation into aquaculture diets, yet such technologies are lacking in the region. The high costs associated with these technologies and energy inputs further complicate the situation, necessitating the exploration of low-cost sustainable energy options like solar and hydropower.

The limited production of single-cell proteins (SCPs) and the reliance on expensive electricity for aquaculture operations restrict the availability and quality of feed ingredients, undermining rural aquaculture development.

Despite the presence of diverse insect species in Africa, the insect farming industry remains underdeveloped due to insufficient investment in technology and a lack of skilled personnel. Furthermore, the inaccessibility of animal by-products for commercial aquafeed production poses significant environmental challenges, including greenhouse gas emissions from poorly managed waste.

The absence of advanced processing technologies significantly restricts the scalability of alternative protein production in Africa's aquafeed industry, limiting the potential for growth and sustainability in aquaculture.

4.7 POLICY REGULATIONS

Growing the aquafeed sector in Africa requires a strategic policy-based model to reset the industry's priority for increased productivity. Despite the relevance of alternative proteins in expanding the aquafeed industry, the alternative protein industry is experiencing significant policy-related challenges in Africa. Alternative protein producers face critical challenges, such as production rights, licenses, sales, and procurements, due to bureaucratic bottlenecks. The potential for alternative protein investment in Africa is currently not being fully realized despite the substantial economic benefits it promises.

It could be attributed to weak policies and an unpredictable business climate (Inflation, economic downturn) that could deter potential investors. Furthermore, inconsistent policy regulations, political bias, and poor cooperation among member states constitute significant setbacks to the industry's growth.

In most African countries, alternative protein production and associated rules of engagement are not policy-oriented and, therefore, may not contribute significantly to the growth of the industry. However, another significant constraint is the lack of information and documentation regarding the operations of alternative protein industries in the region, hence limiting accurate statistics for proper policy legislation, regulation, periodic appraisal, and validation. For example, there is no comprehensive scientific data about SCP and insect production in Africa, except for the survey of Tanga and Kababu, whose report was based on estimation at the time of the current study. Regarding alternative protein production, some African countries are not producing at maximum capacities. This could be due to a lack of policy-based support to strengthen their operations and contribute to the growth of the alternative proteins market in Africa.

4.8 SOCIOECONOMIC IMPACTS

Using alternative protein-based feed sources in the aquafeed industry is a unique opportunity to boost food production and meet the growing demand for food, particularly in the current era of the global food crisis. As the United Nations predicts thatthe global population will reach 9.7 billion by 2050, targeted investment in alternative protein sources for robust aquaculture production is crucial to promote food security and nutritional health.

The shift toward alternative protein sources in aquaculture could create many employment opportunities through the production value chain. Alternative protein production involves stages of production tasks ranging from research and development of products to production and testing of the feed products to ascertain their effects on fish nutrition performance.

This requires a relative workforce from various skill backgrounds (aquaculture scientists, technicians, biotechnologists, policymakers, supply chain specialists, and food nutritionists) to work at the different stages along the production chain, such as the cultivation, processing, logistics, supply chain, policy, and regulation, therefore creating job opportunities, within the industry.

Additionally, expanding the alternative protein industry can offer valuable opportunities for investment in new infrastructure and local supply chains to support smallholder farmers and regional groups, especially women and youth.

More importantly, creating job opportunities is expected to reduce the unemployment rate, particularly in Africa, estimated at 5.3% – 7.0% by the United Nations, and enhance the African GDP, estimated at 3 trillion USD.

4.9 SOCIAL ACCEPTANCE OF ALTERNATIVE PROTEINS

Many alternative proteins have garnered increased attention in recent years, and their potential economic, nutritional, and environmental benefits have mainly been acknowledged. However, concerns and criticisms exist regarding the sources and propagation methods of some alternative proteins, which may conflict with cultural, social, and religious norms and beliefs, affecting their acceptability as feedstuffs for aquafeed in some parts of Africa. For instance, genetically modified (GM) plant proteins can be a valuable source of protein for aquafeed. Although GM plant proteins are cultivated in some African countries like Egypt, Burkina Faso, and South Africa, they still face severe criticism as protein sources for aquafeed following the negative connotations toward products that have been modified genetically due to the possibilities of their potential toxicity, allergenicity, potential unintended effects, and risk of horizontal gene transfer to other species.

Based on tribal and cultural sentiments, some people are skeptical about using GM proteins in aquaculture diets, as they could contaminate the diets and animals. There is poor acceptance of GM protein (soybean, corn gluten, cottonseed) products in some parts of Africa due to the speculated health risks in recipient fish and humans largely. Other motivators include a lack of trust in science, neophobia, and poor media coverage. It is also speculated that applying a novel gene in a modified plant could disrupt endogenous gene expression, leading to inadvertent or unplanned effects like changes in nutrient levels and plant toxicants (ANFs). However, genetic modification offers the possibility to tailor the plant to the nutritional requirements of different fish species. This could be highly relevant considering the expensive and challenging process of reducing anti-nutritive factors in plants or elevating their protein content.

5. SOLUTIONS AND RECOMMENDATIONS

The key solutions and recommendations for enhancing the availability and utilization of alternative proteins in Africa's aquaculture sector. It highlights the importance of policy reforms, investment in research, technological advancements, and regional cooperation to drive sustainable aquaculture practices and improve food security, economic growth, and environmental conservation.

This study identifies that while alternative proteins are theoretically available and more affordable than fishmeal, they remain underutilized in commercial aquaculture due to various challenges. To promote sustainable aquaculture in Africa, it is crucial to improve the availability of these proteins through significant reforms.

POLICY AND REGULATORY FRAMEWORK

An evidence-based policy framework is essential to drive reforms in the alternative protein industry. This framework should aim to:

Liberalize bureaucracy and promote development.

Stimulate innovation and create investment opportunities.

Ensure equitable conditions for alternative protein producers and investors.

Strengthen socioeconomic infrastructure and liberalize taxation on trade and imports.

INVESTMENT AND FUNDING

To overcome setbacks in the aquafeed sector, substantial funding for alternative protein production is necessary. This includes:

Allocating funds for research on alternative proteins and feed raw materials.

Defining core priority areas for research and innovation.

AGRICULTURAL PRACTICES

Encouraging farmers to adopt improved seed varieties for protein crops can enhance production. Solutions to conflicts between crop farmers and herders may include:

Training programs designed for the improvement of skills.

Establishing ranching schemes and fodder banks.

TECHNOLOGICAL ADVANCEMENTS

Upgrading processing infrastructure and production technologies is vital. Key recommendations include:

Transitioning to modern processing methods to explore diverse alternative proteins. Implementing advanced technologies to improve protein quality and reduce contamination.

Utilizing AI and nutritional programming to optimize feed ingredients and enhance fish health.

SUSTAINABLE ENERGY

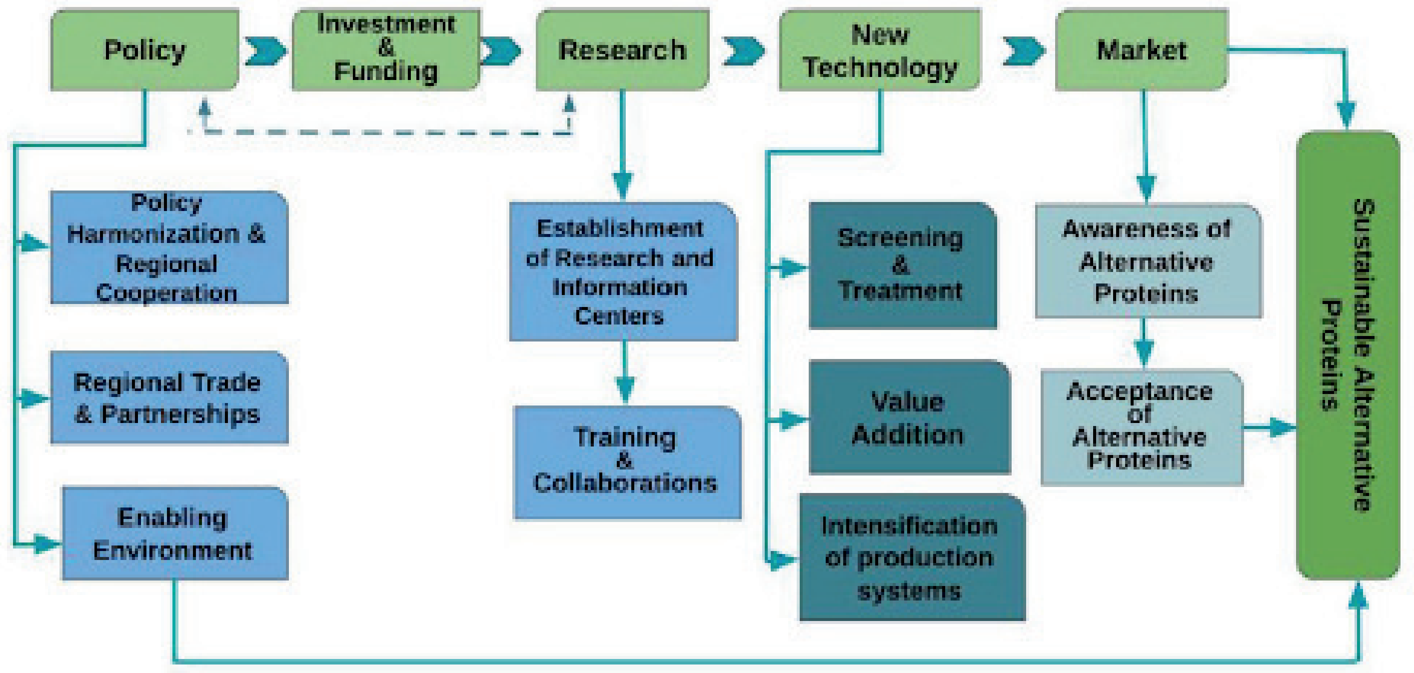
Adopting sustainable energy sources, particularly solar energy, can reduce costs and environmental impact. This shift can facilitate a more sustainable aquafeed industry in Africa.

AWARENESS AND MARKETABILITY

Raising awareness about the benefits of alternative proteins is crucial for social acceptance and market growth. Ensuring affordability will help make these proteins accessible beyond aquaculture.

COLLABORATIVE EFFORTS

The transformation of Africa's aquaculture feed sector requires collaboration among stakeholders, policymakers, and researchers to address challenges and implement necessary changes. Addressing the challenges facing the alternative protein industry in Africa necessitates a multifaceted approach involving policy reform, increased investment, technological innovation, and enhanced cooperation among various stakeholders.



6. CONCLUSION

The African aquaculture sector must move towards alternative proteins to ensure sustainability and economic viability.. The overexploitation of forage fish for fishmeal poses environmental risks and could hinder the sector's growth.

While alternative proteins, particularly animal by-products, show promise due to their cost-effectiveness and nutritional quality, challenges remain.

Plant proteins, though inexpensive to produce, face issues such as competition with human food and susceptibility to climate change.

Insect and microbial proteins offer potential but require further research and development. To fully leverage these innovative protein sources, Africa's aquafeed sector needs substantial policy support, funding, and advancements in processing technologies.

Additionally, raising awareness and addressing social acceptance are crucial for integrating alternative proteins into the market. African aquaculture needs focused investments to improve its processing technology, infrastructure, and research to exploit the immense potential of alternative proteins.

Synergy among stakeholders, researchers, alternative protein farmers, and the government at various levels is critical to achieving the desired positive changes in the sector.

Source : S. Iheanacho, S. C. Hornburg, C. Schulz, and F. Kaiser, "Towards Resilient Aquaculture in Africa: Innovative and Sustainable Aquafeeds Through Alternative Protein Sources," Reviews in Aquaculture 17, no. 2 (2025): e13009.

HOW TO BALANCE SUSTAINABILITY AND PALATABILITY OF AQUACULTURE FEEDS IN AFRICA

By : Dr Mustapha ABA. Aquaculture Scientific Expert. Fish Nutrition. Rabat Morocco.

To encourage the sustainability of aquaculture and reduce fish production costs, fishery products must be replaced by sustainable ingredients in aquaculture feeds.

Improving the palatability of low-fishmeal aquaculture feeds is essential to the sustainability and economic viability of aquaculture in Africa. Incorporating feed additives that act as palatability enhancers is a strategy that enables aquaculturists to produce palatable and less polluting feeds, thus contributing to the growth and success of the sustainable aquaculture sector in Africa.

INTRODUCTION

Global population growth, concerns about food security and an increasingly intense interest in environmental sustainability are among the main challenges facing countries in the coming decades (Aryal et al., 2022).

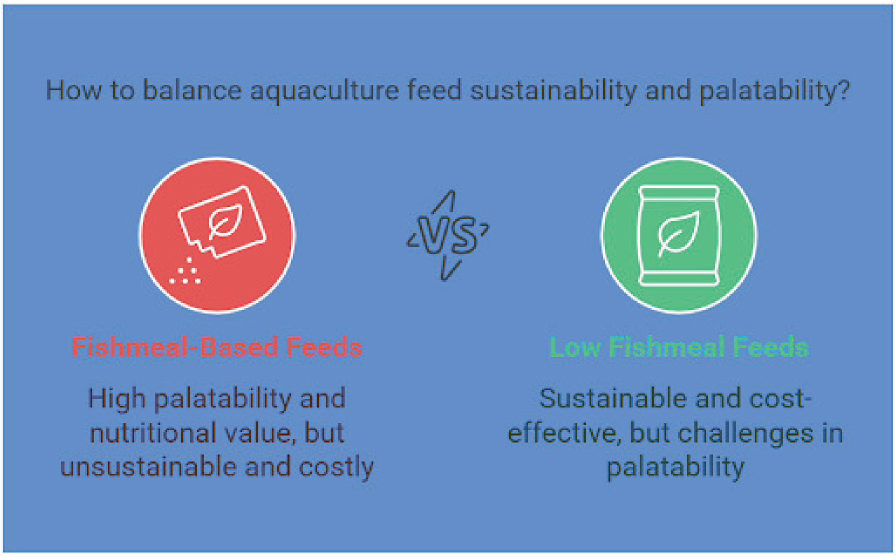
According to the FAO (2024), for the first time, aquaculture dominated global fish production, reaching an unexpected 130.9 million and accounting for 51% of total aquatic animal production.

In Africa, production volumes have increased by a massive 455% since 2000, with the highest growth rate in the world (FAO, 2024).

Aquaculture plays a crucial role in improving food security and creating jobs, particularly in developing regions, especially in Africa. Moreover, this industry has been producing aquatic foods at a growth rate of 7.5% per year since 1970 (Fiorella et al., 2021). This growth in aquaculture production has been facilitated by the rise of intensive feed-based fish farming systems (Fawole et al., 2019).

Fish feed plays a fundamental role in maintaining aquaculture production in all 5 continents, given that it represents the most expensive part of the aquaculture system, accounting for around 60% of total production costs (Craig et al., 2017; Daniel, 2018; Musuka et al., 2023).

A significant proportion of the costs involved in farmed fish production are related to feed and feeding, due to the high cost of protein-rich ingredients (Ansari et al., 2021; Tilami et al., 2020; Wan et al., 2019). Yet the upward trend in the cost of fish feed poses a challenge in intensive farming systems (Haider et al., 2016; Iqbal et al., 2020; Bjørndal et al., 2024), especially with the growth of aquaculture, which has led to an increased need for high-quality fish feed, of which fishmeal is an essential component. (Ansari et al., 2021).



This article highlights the role of palatability enhancers and the sustainability aspects associated with their use as a viable alternative to low fishmeal feeds in the aquaculture industry to ensure fish production with profitable management in the future.

FISHMEAL: A RICH NUTRIENT FOR AQUACULTURE FEEDS

Aquaculture feed represents high operational costs, with protein ingredients responsible for the bulk of its value (Zho and Yue, 2012; Aba, 2020). Protein is often the most expensive component of aquaculture feeds and contributes significantly to overall production costs (Pearce et al., 2004; Dworjanyn et al., 2007; Al-Souti et al., 2019).

Among protein feed sources, it is worth noting that fishmeal is an ingredient that makes up most animal-derived protein sources especially fish feed (FAO, 2025), containing around 60-72% highly digestible protein with a well-balanced amino acid (AA) profile (Pilmer et al., 2022).

According to FAO (2024), in 2021, the aquaculture sector was the main consumer of fishmeal and fish oil produced worldwide (Figure 1), with the remainder of production used for livestock, such as pigs and poultry, and other sectors, such as the pet food market.

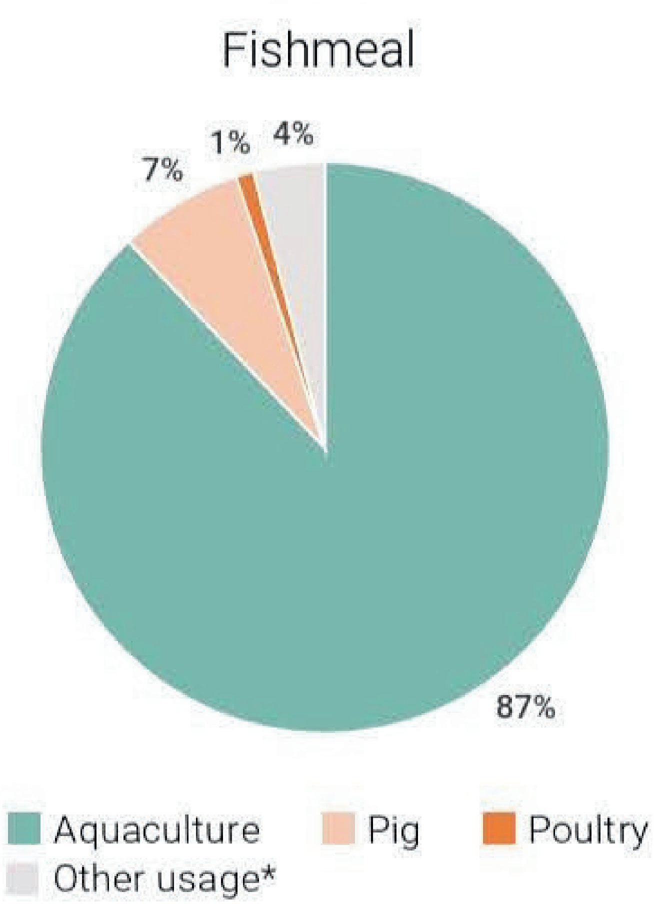


Fig 1 : Fishmeal production in 2021 (FAO, 2024)

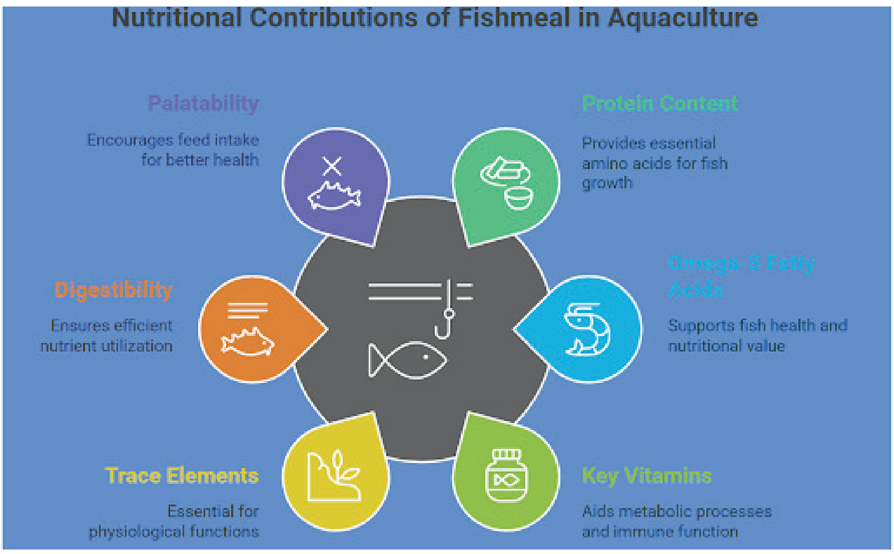
In the aquaculture sector, the incorporation of fishmeal into aquaculture feeds varies according to the species produced, the quality, availability and cost of the ingredient, and the life stage of the farmed species, with early life stages requiring higher levels (FAO, 2025).

African fishmeal production is equivalent to around 8% of world production, but only 1.5% of world production is used as a feed ingredient in Africa (Iheanacho et al., 2025), due to its cost, its export to Asian countries and the weak aquaculture feed industry in Africa, with the exception of Egypt.

Fishmeal is renowned for its nutritional quality, offering a balanced profile of amino acids (Pilmer et al., 2022), omega-3 polyunsaturated fatty acids and essential vitamins and minerals, and is free from anti-nutritional factors with high palatability and digestibility (Bhuyain et al., 2019). The digestibility and palatability of fishmeal make it an excellent choice for livestock feed, ensuring optimal growth and health (Pilmer et al., 2022, Hussain et al., 2024; FAO, 2025).

The good growth of aquatic species when fed diets containing fishmeal results from :

- Good protein content with a good balance of amino acids.
- Good protein digestibility
- Good feed palatability
- Absence of anti-nutritional factors
- Sufficient omega-3 content
- Better vitamin and mineral intake.



Fishmeal is essential for the rapid development of farmed fish, with around 30-40% fishmeal in fish feeds to meet the necessary requirements (Hardy et al., 2022; Alfiko et al., 2022; Boyd et al., 2022). The use of fishmeal as the main source of protein in aquaculture feeds is precarious as its production from nature continues to decline each year, making it expensive to supply (Rosa et al., 2019; Ndebele-Murisa et al., 2024).

PALATABILITY

In fish, taste is responsible for the detection and approval of foods present in the environment or absorbed in the mouth (Hansen and Reutter, 2004). The stimulatory quality of the food, which determines acceptability by the target animal, is known as palatability, which is a key concern when developing artificial diets for aquaculture (Dworjanyn et al., 2007).

Palatability indirectly affects consumption and digestibility by making food more or less attractive to fish (Bowker, 2013). It is well known that plant-based alternative protein ingredients cause palatability problems in carnivorous marine fish, and that reduced feed intake due to unfavorable taste leads to impaired growth performance (Nagel et al., 2012).

PALATABILITY IN AQUACULTURE NUTRITION

In aquaculture, how the animal accepts food is often used as the basis for defining palatability (Glencross, 2020), making palatability a key concern when developing artificial diets for aquaculture (Dworjanyn et al., 2007). Palatability indirectly affects consumption and digestibility by making food more or less attractive to fish (Bowker, 2013).

If a food is inedible, the result will be a large amount of waste from uneaten/undigested food and poor performance (growth and quality) of the organism. Inedible diets cause fish to become satiated more quickly and consume less food, which in turn reduces their growth within the allotted time.

Alternatively, a more palatable feed will be more readily consumed and therefore lower proportions of expensive feed components, such as protein, will be required.

SUSTAINABILITY AND AQUACULTURE PRODUCTION

The key factor affecting the sustainability of the aquaculture industry is access to high-quality ingredients at a reasonable price (Ghosh and Ray, 2017; Goswami et al., 2020). In this context, and in order to maintain aquaculture growth in the face of a stable fishmeal supply, there is a need to identify more suitable and sustainable protein ingredients that maintain fish performance and health (Kobayashi et al., 2015; Tacon & Metian, 2008, 2015), especially with a higher cost and fluctuating FP supply following the depletion of aquatic resources and the changing dynamics of fishmeal supply and demand (Huang et al., 2023). All these factors, necessitate replacing this valuable ingredient with cheaper alternative protein sources with acceptable amino acid composition (Santigosa et al., 2011; Al-Thobaitia et al., 2018). Consequently, it is now imperative to look for alternative protein sources to replace FP for the sustainability of aquaculture (Hussain et al., 2024).

However, replacing fishmeal with plant proteins has a direct impact on the palatability of diets. Commercially important aquaculture species, such as Pacific white shrimp (Litopenaeus vannamei) and carnivorous fish, are less likely to consume diets containing plant proteins due to their low attractiveness and palatability (Nunes et al., 2006; Terrey et al., 2021.

To ensure sustainable aquaculture, the incorporation of plant proteins in carnivorous and omnivorous fish has been the main alternative to fishmeal, mainly due to their stable availability, relatively low cost and relatively good nutritional composition (although requiring supplementation with essential amino acids) (Kissinger et al., 2016).

Nevertheless, excessive amounts of plant protein ingredients in carnivorous fish diets reduce feed palatability, which in turn affects fish feed intake (AI), thus affecting their growth performance (Aksnes et al., 2006).

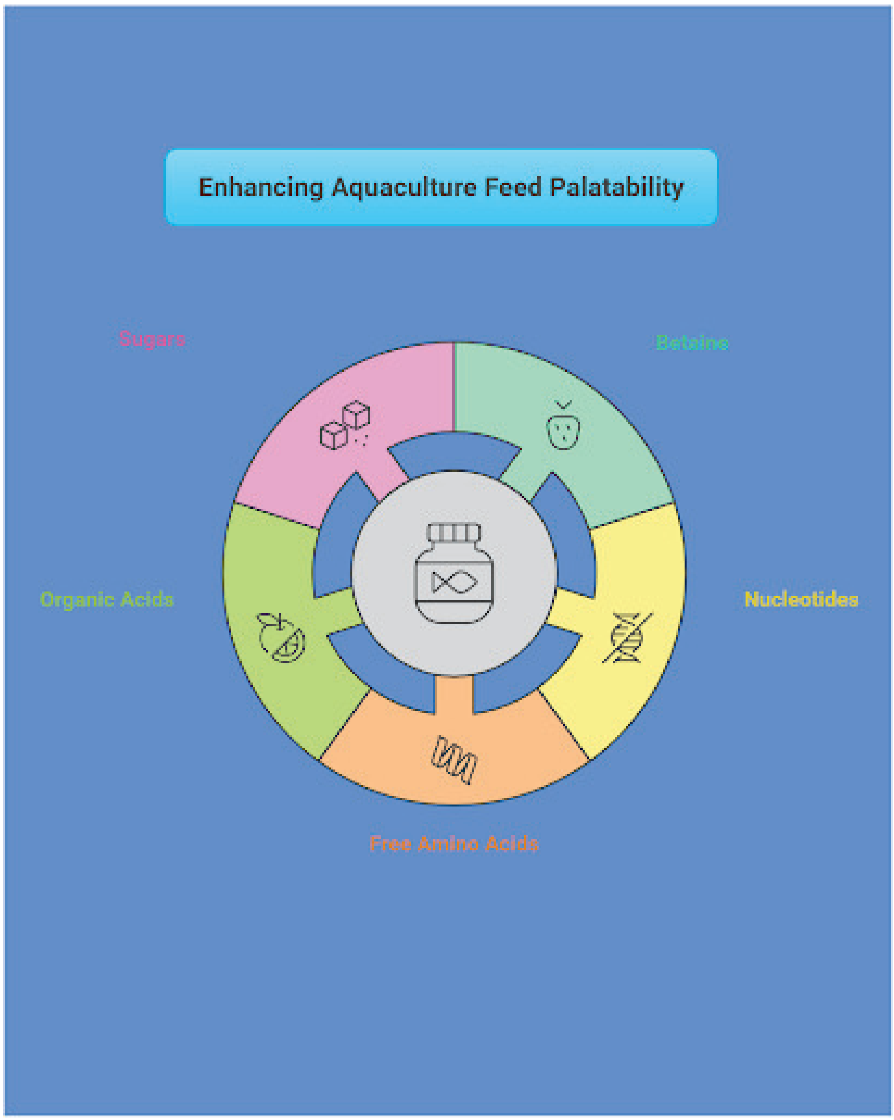
To improve palatability and stimulate fish feeding, attractants are used, which are non-nutritive feed additives that act on the olfactory and gustatory chemosensory systems of fish to induce them to eat, thereby improving their feeding behavior (Kolkovski et al., 2000, Singh et al., 2024), improving feed efficiency, reducing feed waste, leading to a substantial reduction in feed costs and organic pollution (Morais, 2016).

Various types of palatability enhancers have been tested, including krill hydrolysate, krill meal, dimethyl-β-proprotein, dimethylthetin, tryptophan, taurine, betaine, squid hydrolysate, squid meal, stick water, squid paste, among others (Kolkovski et al., 2000; Zhi et al., 2025).

PALATABILITY ENHANCERS

The palatability of aquaculture feeds is the main concern of feed manufacturers, as it can directly influence the yield of aquaculture production.
In the field of fish nutrition research, the palatability of feed is primarily evaluated by carefully measuring the amount of feed intake and by monitoring the resulting growth performance over time (Glencross et al., 2007).

In this context, any compound that can increase the palatability of an animal feed is referred to as a palatability enhancer, such as fish meal, fish oil, krill meal, squid liver meal, shrimp meal, algal meal and protein hydrolysates, are recognized as highly palatable ingredients in aquaculture (Nunes et al., 2006; Al-Souti et al., 2019).



In low fishmeal feeds, improving the palatability of aquaculture feeds is a multifaceted challenge that requires a holistic approach; carefully selecting and blending alternative protein sources, optimizing processing methods and using palatability enhancers, which are functional additives for aquaculture feeds with attractive properties that can improve the palatability of diets, by acting on the olfactory and gustatory chemosensory systems of fish (Kolkovski et al. , 2000, Claus and Sorensen, 2017).

BETAINE

Betaine is one of the most widely used attractants in feed formulations. Its incorporation into aquaculture feeds has a positive influence on several growth parameters and feed utilization by aquatic animals (Li et al., 2024; Mugwanya et al., 2024).

NUCLEOTIDES AND NUCLEOSIDES

These additives improve diet palatability and stimulate eating behavior. (Li et al., 2015; Prasad et al., 2020).

FREE AMINO ACIDS

Free amino acids have been used as functional feed additives that can stimulate feed intake in aquaculture, particularly in diets containing few marine ingredients (Kasumyan and Doving, 2003; Wangkahart et al., 2023).

L-carnitine is a free amino acid with great potential as a feed attractant in fish and shrimp diets with increased feed intake, growth and feed efficiency (Harpaz, 2005).

In addition to L-carnitine, other free amino acids such as L-alanine, L-cysteine, L-serine, L-glutamine, L-glycine, L-glutamic and L-tyrosine have also shown stimulatory effects in fish.

ORGANIC ACIDS

Organic acids represent a specific category of feed additives that have the ability to enhance the palatability of feed, which in turn can lead to a noticeable increase in feed consumption and, ultimately, contribute to an improvement in overall growth performance (Ng and Koh, 2017).

Several studies have shown improved growth performance and feed utilization in trout, carp , tilapia, shrimp, when fed organic acids, such as butyrate, oxalic acid, malic acid, citric acid, formic acid and propionic acid (Fabay et al. 2022).

SUGARS

Dietary carbohydrates may facilitate pellet binding and improve stability and palatability (Honorato et al., 2010).

CONCLUSION

In aquaculture, the limited supply of fishmeal worldwide has prompted the feed industry to adapt by seeking alternative protein sources. However, the success of these feeds will depend on key properties, including nutritionally complete formulation, nutrient availability and feed palatability. In order to balance the sustainability of aquaculture through low fish meal use and improved feed palatability, exogenous feed additives are used in fish nutrition to minimize feed palatability problems, for efficient nutrient use, reduced economic losses in aquaculture, improved performance of aquatic species and reduced feed waste to ensure more sustainable aquaculture in Africa.

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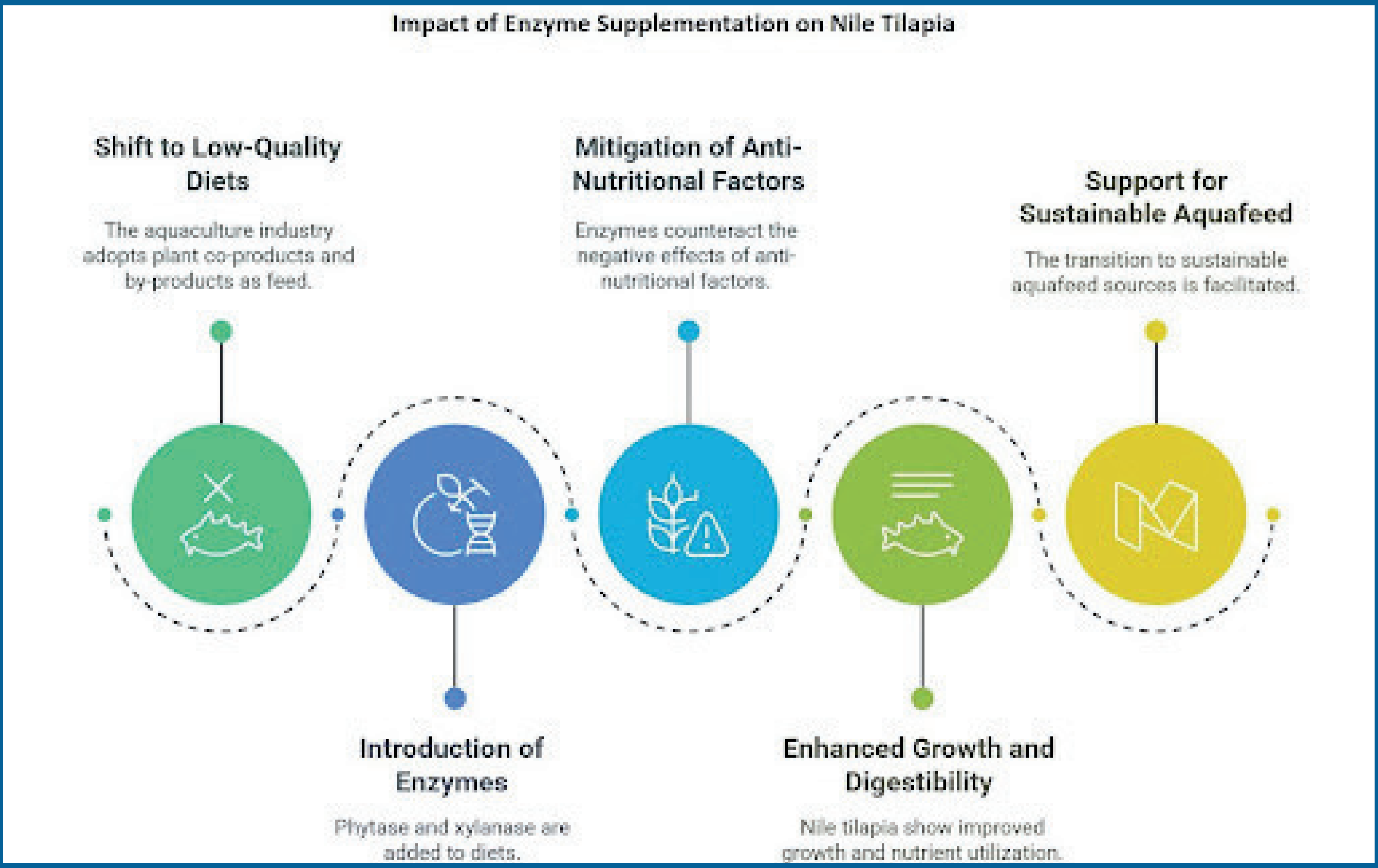
ENZYME SUPPLEMENTATION (PHYTASE AND XYLANASE) IMPROVES LOW QUALITY DIETS IN NILE TILAPIA



By Roel M.Maas, Fotini Kokou, Marc C.J Verdegem and Johan W Schrama. Aquaculture and fisheries group, Wageningin University and Research, Wageningin the Nederlands

En raison de la demande croissante d'ingrédients pour l'aquaculture qui n'entrent pas en concurrence avec l'alimentation humaine, les co et sous-produits végétaux, et donc les facteurs antinutritionnels tels que les polysaccharides non amylacés et les phytates, devraient augmenter. Les enzymes endogènes qui ciblent les facteurs antinutritionnels peuvent faciliter cette transition. Cette étude a examiné si des ingrédients de faible qualité affectent les effets des enzymes endogènes sur la croissance du tilapia du Nil (Oreochromis niloticus), l'utilisation des nutriments, le microbiote et les caractéristiques du digesta.

Enzyme supplementation was successful in improving growth, digestibility, and nutrient utilization, with the effect often being stronger for the lower-quality diet. Thus, the lower-quality diet's larger enzyme supplementation improvement may help transition to ingredients that compete less with human food.

1. INTRODUCTION

To meet the growing demand for aquafeeds, the use of low-quality ingredients in aquafeeds that do not compete with human food is expected to increase, as will the use of formulated aquafeeds containing plant ingredients that would otherwise be wasted (FAO, 2020). The levels of anti-nutritional factors such as phytate and non-starch polysaccharides (NSP) are expected to rise as plant by- and co-products increase; phytate is the main storage form of phosphorus (P) in plants, and NSP consists of remnants of plant cells, which are mainly found in the cell walls of plants and often referred to as fiber (Dhingra et al., 2012; Sinha et al., 2011; Hossain et al., 2024). Increasing levels of both phytate and NSP showed to reduce the growth performance of fish mainly due to reduced nutrient digestibility (Haidar et al., 2016; Maas et al., 2020).

Both phytase and NSP-degrading enzymes offer potential tools for (partially) mitigating the negative effects of phytate and NSP by breaking them down and increasing their digestibility (Kumar et al., 2012; Castillo and Gatlin, 2015; Zheng et al., 2020). For example, phytase has been shown to be effective in improving growth and P availability for multiple fish species, including different carp species (Major carp (Labeo rohita) (Hussain et al., 2017) and Mrigal (Cirrhinus mrigala) (Hussain et al., 2015), salmonids (rainbow trout (Oncorhynchus mykiss) and Atlantic salmon (Salmo salar) (Greiling et al., 2019) and Nile tilapia (Oreochromis niloticus) (Maas et al., 2018).The role and importance of feed enzymes such as phytase and xylanase are expected to grow as the level of low-quality ingredients in aquafeeds increases. This is because the improvement in growth and digestibility with enzyme supplementation is expected to be more evident as the levels of anti-nutritional factors such as NSP and phytase increase. This is particularly relevant for low value fish species (and thus low-quality diets) like Nile tilapia, which has omnivorous feeding habits and can tolerate high plant material levels (i.e., high NSP levels) (Tesfahun and Temesgen, 2018).

As seen in Nile tilapia, NSP can impact on the characteristics of the digesta within the gut, such as its viscosity and dry matter content (Leenhouwers et al., 2007a). In addition, several studies have demon strated that the dietary composition can influence the gut microbiota in fish by altering diversity and composition (Pedrotti et al., 2015; Ringø et al., 2006, 2016), with potential implications for gut health and feed utilization. When NSP is degraded into less polymerised compounds, they become available for fermentation by microbiota, resulting in the production of Volatile Fatty Acids (VFA) (Castillo and Gatlin, 2015). Tilapia has, as a predominantly herbivorous warm-water fish with a long gut, the potential for gut fermentation (Metzler-Zebeli et al., 2010; Maas et al., 2021). The addition of exogenous enzymes is expected to enhance NSP breakdown and thus VFA production, increasing NSP digestibility. Several studies have demonstrated that enzymes can improve NSP digestibility (Maas et al., 2018; Maas et al., 2019; Maas et al., 2020), where NSP is used as a catch-all term. However, NSP can be divided into many types and structures that can be identified by their constituent sugars. Information on which fraction of NSP (constituent sugar) endogenous enzymes act in fish is lacking. Moreover, differences in potential substrate (both composition and level) for gut fermentation can have an impact on VFA production (Leenhouwers et al., 2008; Liu et al., 2022) and composition (Macfarlane and Macfarlane, 2003). The main VFA produced in fish are acetate, propionate, and butyrate, with acetate and propionate being quickly absorbed and used as energy sources, while butyrate serves mainly as a direct energy source by colonocytes (Maas et al., 2020). Because fermentation occurs via microbial anaerobic glycolysis, a shift in microbiota can be expected. Furthermore, produced VFA can act as metabolites in the gut and fluence the gut microbiota, but also gut health (Wen et al., 2018; Kazlauskaite et al., 2022).

Therefore, our understanding of how microbiota alterations can interfere with fish performance and feed efficiency is currently lacking, as only limited studies have evaluated microbiota composition in conjunction with VFA content in the gut.

Moreover, little is known about whether increasing the level of low-quality ingredients (and thus the level of NSP and phytate) affects the potential effect of endogenous enzymes on fish performance and nutrient utilization.

Considering the above, the current study examined the impact of enzyme supplemen tation on growth performance, nutrient utilization (including gestibility), microbiota, and digesta characteristics (i.e., viscosity, pH, and VFA content) along the gastrointestinal tract (GI-tract) in diets varying in quality and thus phytate and NSP levels.

2. METHODOLOGY

Four experimental diets were tested in a 2 × 2 factorial design, where the first factor was the level of low-quality ingredients (control versus high), and the second factor was enzyme supplementation (xylanase and phytase versus no supplementation). After a 42-day feeding trial, fish were belt-fed for 4–6 days to collect digesta along the gastrointestinal tract.

3. RESULTS

3.1. PERFORMANCE

The study found that crude protein intake was consistent across experiments. Reduced diet quality led to decreased performance parameters, while enzyme supplementation improved growth, feed conversion ratio (FCR), and daily growth coefficient (DGC). Notably, enzyme supplementation had a more pronounced effect on the low-quality diet, improving FCR from 1.33 to 1.19.

3.2. DIGESTIBILITY

The low-quality diet significantly reduced the digestibility of various nutrients; of dry matter (DM), energy, protein, fat, total carbohydrates, starch, and the minerals phosphorus, calcium, and magnesium.

Enzyme supplementation improved the digestibility of dry matter, energy, and minerals, resulting in a 37% increase in phosphorus availability.

The interaction between diet quality and enzyme supplementation was significant, particularly for NSP (non-starch polysaccharides) digestibility.

3.3. BODY COMPOSITION

Fish on the control-quality diet exhibited lower body protein content and higher dry matter content.

The low-quality diet resulted in reduced body fat content, which was further decreased with enzyme supplementation.

Enzyme-supplemented diets led to higher levels of ash, phosphorus, calcium, and magnesium.

3.4. NITROGEN, ENERGY, AND PHOSPHORUS BALANCE

The addition of enzymes increased retained N while decreasing branchial and urinary N losses ($P < 0.05$). The increased N retention and decreased branchial and urinary losses resulted in increased N efficiency with enzymes.
The low-quality diet did not significantly affect nitrogen balance, but enzyme supplementation increased nitrogen retention and efficiency.

Enzyme supplementation increased the retained Energy. There was an effect of enzyme supplementation and an interaction effect for the branchial and urinary E loss in line with the branchial and urinary N loss. The enzymes also improved phosphorus retention, with a greater effect observed in the low-quality diet.

3.5. DIGESTA CHARACTERISTICS

Enzyme supplementation increased volatile fatty acid (VFA) content in the distal gut, while the control-quality diet had lower stomach pH.

The dietary treatments did not significantly affect viscosity.

3.6. MICROBIOTA COMPOSITION

Enzyme supplementation influenced the digesta microbial community, decreasing alpha diversity, particularly in the control-quality diet.

4. DISCUSSION

It was investigated whether the potential of enzyme supplementation is dependent on diet quality in light of future changes in tilapia diets towards increased use of low-quality ingredients.
This study highlights the potential of enzyme supplementation to enhance the performance of Nile tilapia fed low-quality diets.

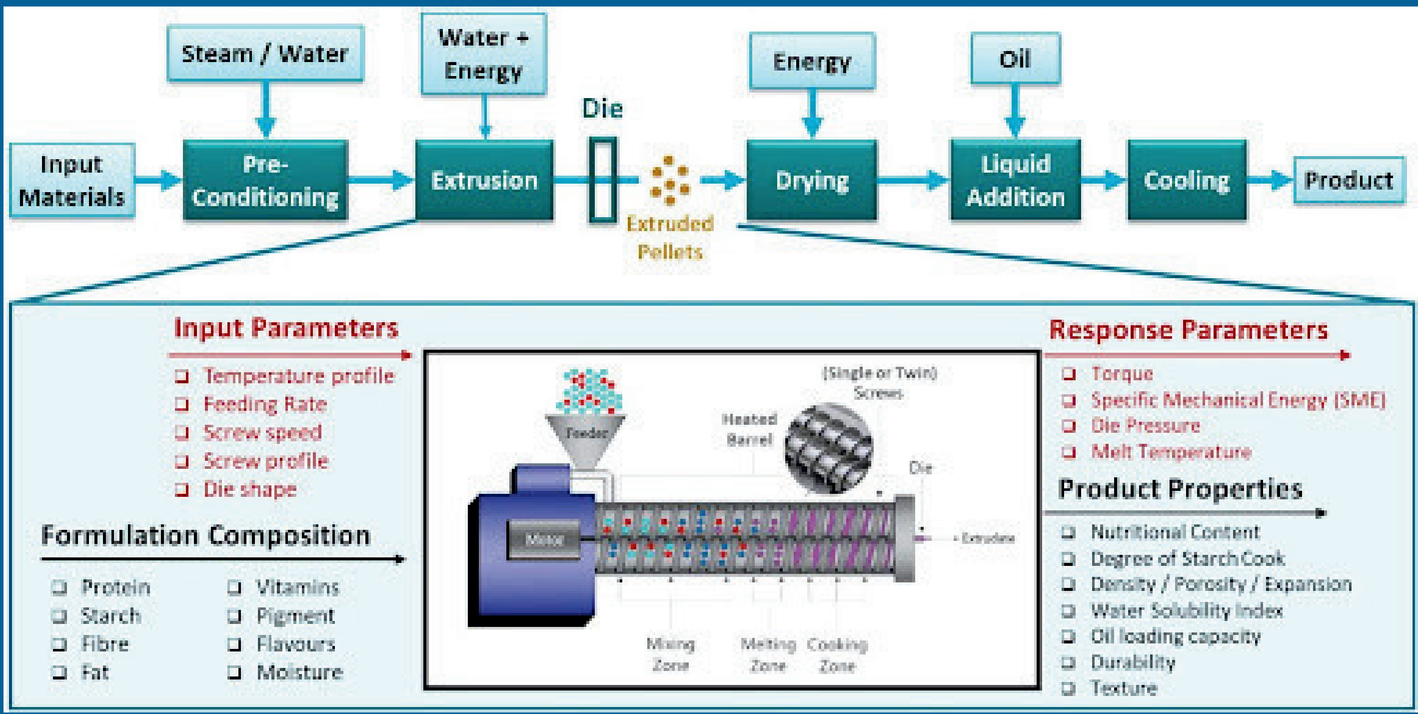
The combination of phytase and xylanase effectively mitigated the negative impacts of anti-nutritional factors, improving growth, digestibility, and nutrient utilization. The findings support the transition towards using more sustainable aquafeed ingredients that are less competitive with human food sources.

CONCLUSION

Enzyme supplementation with phytase and xylanase significantly improves the growth and nutrient utilization of Nile tilapia fed low-quality diets. This approach not only enhances fish performance but also promotes the use of sustainable feed ingredients, aligning with the industry's need for more environmentally friendly aquaculture practices, and highlighting the potential role of enzymes in future feed formulation.

Source : Roel M. Maas, Fotini Kokou, Marc C.J. Verdegem, Johan W. Schrama. Enzyme supplementation (phytase and xylanase) improves low quality diets in Nile tilapia.Aquaculture Reports 40 (2025) 102650

MECHANISMS, CHALLENGES AND OPPORTUNITIES OF AQUAFEED EXTRUSION



This document provides a concise summary of the advancements and challenges in aquafeed extrusion technology, which is crucial for the growth of aquaculture. The demand for affordable energy and nutrients necessitates high-quality feed to ensure productivity and sustainability. Over the last few decades, extrusion technology has proven effective in producing feed with improved attributes like digestibility and buoyancy.

The review discusses the mechanisms of extrusion, challenges in industrial production, and future opportunities, including AI-driven quality control. It also highlights the evolution of feeding techniques and their impact on fish growth. Despite progress, challenges such as ingredient variability and operational complexity persist.

This review offers researchers, technologists and industry stakeholders a comprehensive understanding of the current landscape, challenges and future prospects for extruded aquafeed production

1. INTRODUCTION

The aquaculture sector has seen remarkable growth, with its share of total seafood production rising from about 19.7% in the 1990s to nearly 50% by 2020. This growth is largely attributed to rising global seafood demand, advancements in aquaculture technology, and a focus on sustainable management of wild fish stocks.

China plays a pivotal role in this industry, producing over 48 million metric tons of seafood, which constitutes 60% of global aquaculture output. Aquaculture has become crucial for China's food security, contributing to 80% of its total fish production by 2020.

To support this continuous growth, there is a pressing and increasing need for aquafeed, which plays a crucial role in sustainably meeting the rising global demand for seafood. It is projected that the production of aquafeed will reach 87 million tonnes by the year 2025.

However, feed costs often exceed 50% of total aquaculture production costs, necessitating careful diet formulation that balances nutritional needs with economic factors. The optimization of aquafeed processing is expected to be a key focus area in the future.

2. HISTORICAL DEVELOPMENT OF AQUAFEED

2.1 FEED EVOLUTION

The evolution of aquafeed reflects a complex interplay of scientific, economic, and philosophical changes in aquaculture. Initially, aquaculture relied on natural feed sources, but as productivity demands increased, the industry shifted towards formulated feeds. This evolution can be categorized into three dimensions:

Nutritional Precision: Understanding species-specific dietary needs led to the development of balanced diets that optimize growth and health.
Technological Innovation: The transition from artisanal practices to industrial-scale production introduced advanced feed manufacturing processes, including steam-pressed and extruded pellets. Key advancements include:

- Intensification of operations through selective breeding and improved formulations.
- Enhanced feed processing technology, particularly through extrusion, which allows for tailored pellet buoyancy and improved digestibility.
- Improved shelf stability and safety of feeds, reducing biosecurity risks.
- Automation in feeding and monitoring, increasing production efficiency.

Environmental Considerations: The evolution of aquafeed also reflects growing awareness of environmental impacts and the need for sustainable practices in aquaculture.

2. HISTORICAL DEVELOPMENT OF AQUAFEED

The aquafeed production landscape has transformed significantly since the introduction of high-throughput facilities in the 1950s.

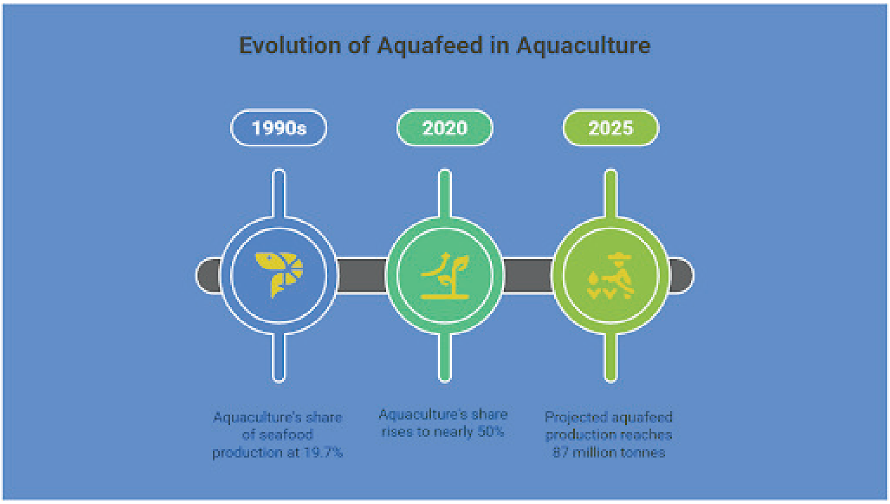
Today, the industry is characterized by a mix of large corporations that dominate global operations and numerous smaller, specialized companies that cater to local markets. Each feed mill operates uniquely, with variations in equipment, product offerings, and procurement strategies.

Larger companies benefit from extensive global supply networks, allowing them to control the trade of specific grains and commodities, while smaller firms focus on local trade, optimizing logistics by situating near transport routes.

Significant advancements have been made in feed production techniques for aquatic species, with pelletisation and extrusion being the two primary manufacturing methods.

Extrusion is the most prevalent method, with projections estimating aquafeed production to reach between 73 and 87 million metric tons by 2025.

The selection of feed type in aquaculture is influenced by several factors, including the nutritional needs of the species, their feeding behaviors, biological maturity stages, and preferences for pellet characteristics.
Additionally, the physical properties of the pellets must align with automated feeding systems and adhere to economic constraints dictated by production budgets.



3. APERÇU DE LA PRODUCTION D'ALIMENTS AQUACOLES

3.1. PELLETISATION TECHNOLOGY

Pelletisation technology for aquafeed emerged alongside advancements in agriculture and pharmaceuticals during the mid-20th century, coinciding with the mechanisation trends following World War II. Pelleted feed has become a staple in aquaculture due to its straightforward and cost-effective production process.

The method typically employs a roller-type press that compresses raw materials through a die plate, resulting in high-density pellets. Although the process can reach temperatures of 80°C, it minimizes the degradation of heat-sensitive nutrients.

However, pelleted feed has drawbacks, including higher density and hardness compared to extruded feed, which may not be suitable for all species and growth stages. Additionally, its low oil loading capacity and poor water stability can lead to significant product loss in the form of dust, prompting the search for alternative manufacturing methods like extrusion.

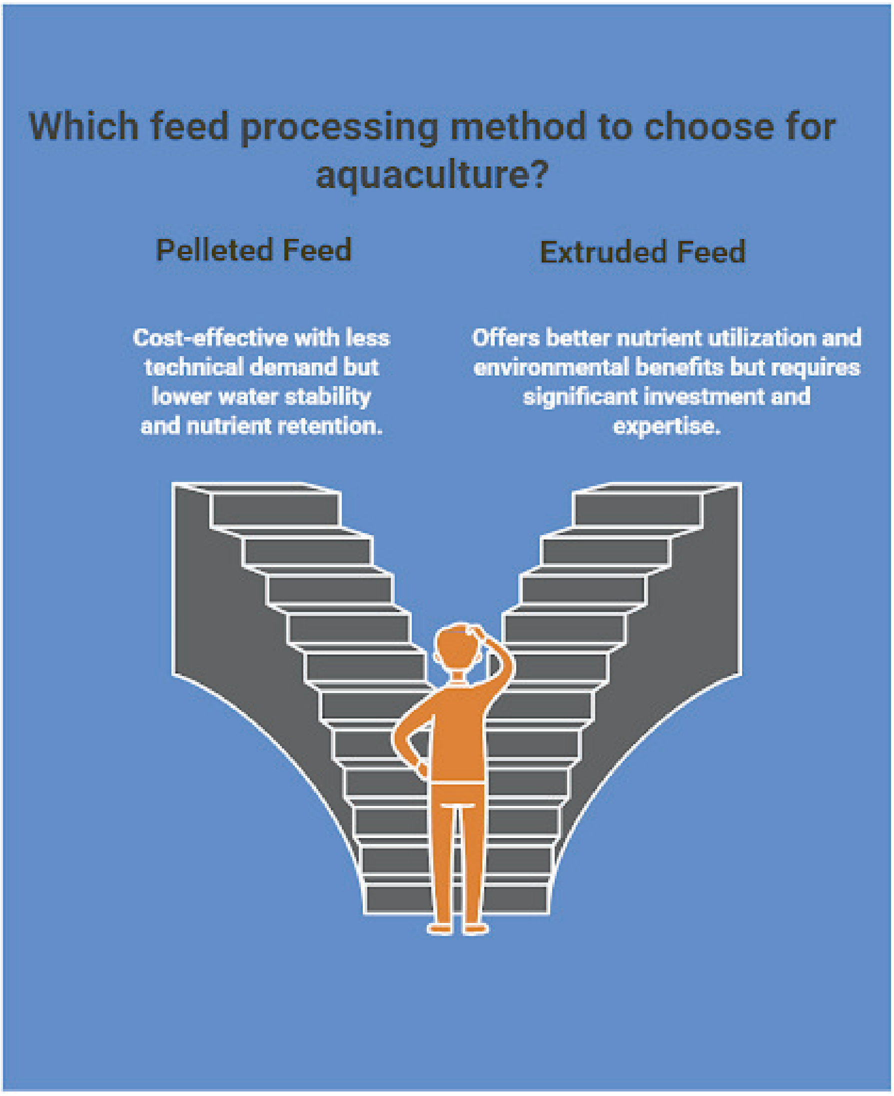
3.2. EXTRUSION TECHNOLOGY

Extrusion technology, adopted in aquafeed manufacturing in the 1980s, utilizes a high-temperature, short-time process that combines heat, pressure, and shear force to create a nutritious and homogeneous product. By the 2000s, it became the preferred method for producing feed for most fish species in developed countries. The extrusion process enhances feed digestibility by cooking starches and proteins, leading to improved nutritional value.

The process begins with a mash of raw materials that is pre-conditioned with steam or water before being fed into a heated extruder barrel. The material is conveyed by rotating screws, which are designed to optimize mixing and cooking through mechanical energy conversion. The final product's characteristics are influenced by various factors, including the composition of the feed mixture and the precise tuning of extrusion parameters such as screw speed and die design.

These elements collectively determine the nutritional content, digestibility, and physical properties of the extruded feed.

3.3. PELLETED VERSUS EXTRUDED FEED



Pelletisation and extrusion both involve a steam pre-conditioning step to improve feed quality and create pellet structures that facilitate transport and handling.

Both methods enhance animal growth performance by improving nutrient utilization. However, pelletisation is a gentler process that forms dense pellets through pressing, while extrusion involves high temperatures and pressures that mix, melt, and sterilize the feed. Extrusion allows for better control over pellet characteristics, such as bulk density and buoyancy, which can be tailored to specific aquatic species.

Extrusion also helps inhibit anti-nutritional factors and enhances the accessibility of nutrients, leading to stronger pellets that minimize dust loss during transport and reduce environmental impacts from uneaten feed.

Additionally, extruded pellets tend to have improved gut retention time, which can enhance nutrient utilization. However, the extrusion process can degrade heat-sensitive vitamins and enzymes, and it requires significant capital investment and technical expertise, which has led to the continued prevalence of pelletisation in shrimp aquaculture.

The advantages and disadvantages of each method are summarized as follows:

Pelleted Feed	Extruded Feed
Regular size and shape	Greater control over bulk density & buoyancy
Relatively easy and cheap manufacturing	Reduced loss of product from pellet dust

High production throughput	Reduced loss of nutrients from pellet breakup in water
Less prone to nutrient loss during processing	Reduced environmental impact from uneaten pellets
Higher density and harder texture	Improved digestibility of protein and starches
Lower oil loading capacity	Heightened capacity for lipid inclusion post-extrusion
Low long-term water stability	Potential degradation of vitamins and dietary enzymes
Product loss (dust) during transportation and feeding	Expensive capital investment for extrusion equipment and Technically difficult to operate extruder.

This detailed comparison provides a more thorough and comprehensive understanding of the specific impacts that both pelleted and extruded feed types have on the overall feed quality and the resulting animal productivity.

4. MECHANISMS OF EXTRUDED FEED

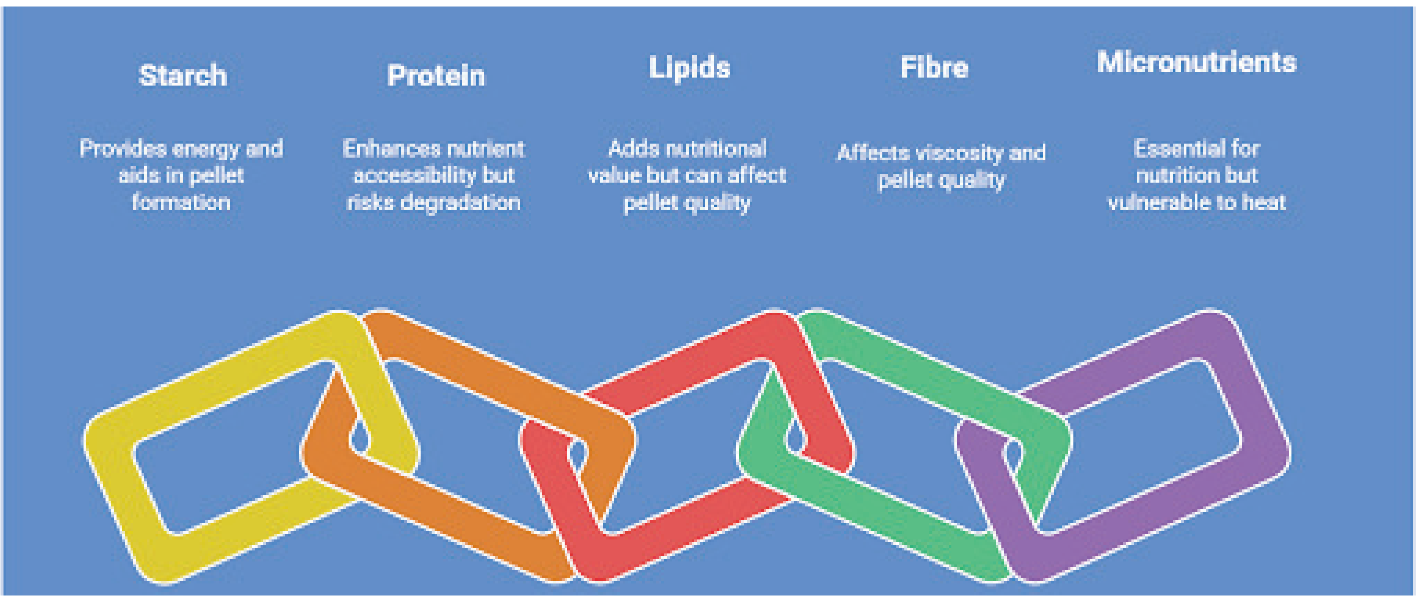
4.1. CONTEXT

The mechanisms of feed extrusion are crucial for enhancing the quality of aquafeed and optimizing production processes for sustainability and cost-effectiveness.

While nutritional quality is often prioritized, the physical quality of feed, influenced by ingredient interactions during extrusion, is equally important.

This section underscores the need for a comprehensive understanding of how extrusion conditions affect pellet quality, which in turn impacts growth performance, body composition, and water quality in aquatic environments.

4.2. INGREDIENT IMPACTS



4.2.1 STARCH

Starch is a key component in aquafeed, providing energy and enabling the formation of durable pellets through gelatinisation during extrusion.

The process involves the disruption of starch molecules, enhancing digestibility and energy availability. Factors such as the amylose-to-amylopectin ratio and granule size affect gelatinisation, which is crucial for pellet quality.

Optimal starch content varies by species, with recommendations for carbohydrate inclusion levels to prevent health issues in carnivorous fish.

4.2.2 PROTEIN

Protein denaturation during extrusion improves the accessibility of nutrients to digestive enzymes. This process is influenced by various factors, including temperature and moisture.

While controlled extrusion conditions can enhance protein bioavailability, excessive processing can lead to degradation and reduced nutritional value.

Further research is needed to identify optimal denaturation levels for different aquatic species.

4.2.3 LIPIDS

Lipids contribute to the nutritional value of feed but can negatively impact pellet quality if present in excess.

Maintaining lipid levels below 12% is crucial to avoid disrupting starch gelatinisation and ensuring proper pellet expansion and texture.

High lipid concentrations can hinder the extrusion process by affecting mechanical energy transfer and cooking efficiency.

4.2.4 FIBRE

The inclusion of plant-based ingredients increases fiber content in aquafeed, which can affect viscosity and disrupt the starch matrix during extrusion.

This can lead to reduced processability and pellet quality. Coarse fibers, in particular, can decrease pellet expansion and increase hardness.

4.2.5 MICRONUTRIENTS

Micronutrients are vital for aquatic nutrition but can be degraded by high temperatures during extrusion.

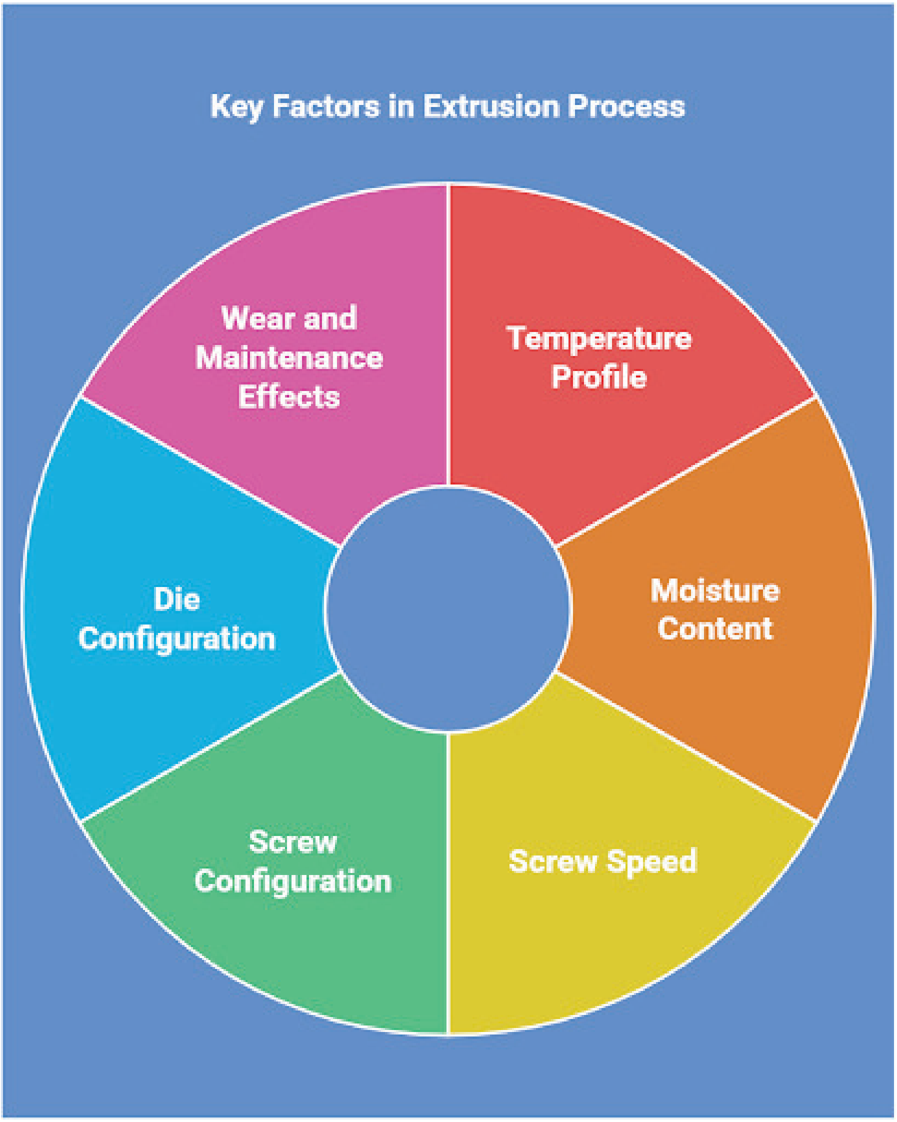
Strategies such as over-fortification or post-extrusion coating may be necessary to maintain their functionality, potentially increasing production costs.

The impact of micronutrients on the extrusion process itself remains an area for further exploration.

4.3. PROCESSING CONDITIONS

The mechanisms of animal feed extrusion are essential for improving fish feed quality and optimizing production processes in terms of sustainability and cost-effectiveness.

Although nutritional quality is often prioritized, the physical quality of animal feed, which results from how ingredients interact during the extrusion process, is also important and should be taken into consideration.



4.3.1 TEMPERATURE PROFILE

The temperature profile is vital in extrusion, affecting the nutritional and physical properties of aquafeed. It typically increases from the feed zone to the die zone, with specific settings based on ingredient types. Proper thermal energy application enhances cooking, starch gelatinization, and feed expansion.

Higher temperatures improve nutrient utilization but can degrade heat-sensitive vitamins and affect pellet quality. Research indicates that increasing extrusion temperature can alter pellet density, oil absorption, hardness, and durability.

4.3.2 MOISTURE CONTENT

Moisture content is crucial for material flow, starch gelatinization, and expansion characteristics. It influences density and expansion through steam generation upon exiting the die.

Low moisture levels (~15%) can lead to high viscosity and overcooking, while high levels (~30%) may reduce cooking efficiency and result in firmer textures.

Optimal moisture content is essential for achieving the right balance between cooking and expansion.

4.3.3 SCREW SPEED

Screw speed affects the mixing, conveying, and shear of the feed mash. It influences the homogeneity of the mixture and, in conjunction with temperature and moisture, dictates cooking and textural properties.

While some studies show minimal impact on pellet density and hardness, others indicate that higher speeds can enhance pellet expansion and durability.

4.3.4 SCREW CONFIGURATION

The screw configuration is critical for mixing, cooking, and shearing intensity. Single-screw extruders have limited flexibility and are sensitive to feed composition changes, while twin-screw systems allow for better control and efficiency. Twin-screw configurations include various elements to optimize material flow and energy input, enhancing the extrusion process.

4.3.5 DIE CONFIGURATION

Die configuration determines pellet size and shape, influencing texture and palatability. The choice of die dimensions is essential for matching pellet characteristics to specific aquaculture species, affecting water penetration and stability.

The configurations of screws and dies are often proprietary, highlighting their importance in the extrusion industry.

4.3.6 WEAR AND MAINTENANCE EFFECTS

The temperature profile is vital in extrusion, affecting the nutritional and physical properties of aquafeed. It typically increases from the feed zone to the die zone, with specific settings based on ingredient types. Proper thermal energy application enhances cooking, starch gelatinization, and feed expansion.

Higher temperatures improve nutrient utilization but can degrade heat-sensitive vitamins and affect pellet quality. Research indicates that increasing extrusion temperature can alter pellet density, oil absorption, hardness, and durability.

4.5 PRODUCT ATTRIBUTES

4.4.1 POROSITY AND DENSITY

Porosity indicates the presence of voids in extruded pellets, affecting water uptake and stability.

High porosity can lead to rapid breakdown in water, while low porosity may hinder oil loading and increase sinking rates.

Bulk density measures the mass of pellets in a volume, relating to both packing and specific density.

4.4.2 SINKING PROFILE

The physical characteristics of pellets, such as specific density, influence their buoyancy and sinking behavior, catering to various species' feeding habits. Different species require specific pellet densities to optimize feeding efficiency. The extrusion process allows for precise control over these characteristics, enhancing feed performance.

4.4.3 HARDNESS

Hardness measures a pellet's resistance to deformation and is influenced by ingredient types and processing conditions. It is assessed using texture analyzers. While hardness relates to mechanical strength, it does not directly correlate with durability, as hard pellets may be brittle.

4.4.4 DURABILITY

Durability reflects a pellet's resistance to external forces and its ability to maintain integrity during handling, transport, and use.

It is assessed through various testing methods and is crucial for minimizing waste during feeding.

Durability affects gastric evacuation rates, influencing feed intake and growth performance in aquatic species.

4.4.5 WATER STABILITY

Water stability refers to a pellet's ability to resist disintegration in water, which minimizes waste and environmental impact.

Low water stability can lead to health issues in fish, such as abdominal distension syndrome.

4.4.6 PALATABILITY

Palatability affects feed acceptance and consumption by aquatic species. It is influenced by sensory properties and the physical characteristics of pellets.

A palatability index is used to measure feed acceptance, highlighting the importance of texture alongside nutritional content.

4.4.7 DIGESTIBILITY

Digestibility is critical for nutrient absorption and overall growth performance. It is influenced by ingredient quality, processing methods, and species physiology.

Extrusion enhances digestibility by altering the physical and chemical structure of feed ingredients.

5. CHALLENGES FOR AQUAFEED EXTRUSION

5.1 OPERATIONAL COMPLEXITY AND COST

5.1.1 CAPITAL INVESTMENT

Extrusion technology requires significant capital investment, typically around 1.5 to 2.5 times higher than pelletisation for comparable throughput levels and operational capacity.

This investment encompasses not only the extrusion machinery but also auxiliary systems like pre-conditioners and quality control instruments.

Consequently, the lack of comparable extrusion equipment in research and development labs poses scalability challenges for laboratory-scale facilities.

5.1.2 TECHNICAL EXPERTISE

The variable nature of the extrusion process demands a high level of technical expertise. Operators must be well-versed in machinery operation to address issues promptly, minimizing downtime and ensuring product quality.

Continuous adjustments to processing conditions and ingredient formulations are essential, necessitating skilled personnel and further driving up costs.

5.1.3 EXTRUSION PROCESS COMPLEXITY

The complexity of the extrusion process is influenced by various factors, including the specific ingredient formulation, the quality of the raw materials, and the biochemical composition of the feed, all of which contribute to the final product's characteristics.

The interaction between different ingredients can lead to unexpected outcomes, highlighting the need for extensive research and development to optimize feed for animal nutrition, productivity, and sustainability.

5.2 DIVERSITY IN PRODUCT REQUIREMENTS

Aquaculture species have diverse nutritional needs, necessitating tailored feed compositions. Carnivorous species require high protein and lipid content, while omnivorous and herbivorous species can utilize dietary carbohydrates more effectively.

Additionally, different life stages of the same species require varying diets, complicating feed formulation. The digestibility of starch across species further complicates the extrusion process, requiring a deep understanding of the target species' metabolic capabilities.

5.3 NOVEL PROTEIN-RICH INGREDIENTS

The introduction of novel protein sources, such as agrifood by-products and insect meals, presents both opportunities and challenges for aquafeed production. While these ingredients can enhance nutritional profiles, they may negatively affect the functional properties of extruded feed. High lipid and fiber content can complicate the extrusion process, impacting pellet quality and stability. The structural state of proteins also plays a crucial role in extrusion functionality. Native proteins generally perform better than denatured proteins, which can lose solubility and binding capabilities during processing.

Research indicates that excessive heat treatment can compromise protein quality, affecting growth performance in aquatic species. Therefore, ingredient manufacturers must balance processing intensity with the preservation of nutritional integrity.

Adjustments to processing conditions can mitigate some challenges, but these modifications often come with limitations and trade-offs.

Understanding these complexities is essential for optimizing aquafeed extrusion and ensuring high-quality feed production.

5.4. INGREDIENT VARIABILITY

Ingredient variability poses a significant challenge in aquafeed production, as the nutritional content and physical properties of feed ingredients can differ widely due to their origin, seasonality, storage conditions, and pre-processing methods. For instance, plant-based ingredients like crop flour can show variations in protein, starch, and fiber content. Glencross emphasizes that the composition and nutritional values of ingredients often lack crucial details in scientific literature, which can lead to operational inconsistencies during the extrusion process.

This necessitates frequent adjustments to feed formulations, adding complexity and cost to production. A study by Samuelsen et al. found that variability in fishmeal, such as differences in water-holding capacity and particle size, affects extrusion response variables. To address these issues, ingredient suppliers must ensure consistency, while millers should implement advanced monitoring and quality control systems.

5.5. FORMULATION VARIABILITY

Feed manufacturers often face significant variability in formulation composition due to fluctuating ingredient costs and availability, which are frequently driven by macroeconomic factors such as inflation and geopolitical conflicts.

Climate change further complicates this by affecting the availability of key ingredients. As traditional ingredients become scarcer and more expensive, manufacturers are adopting strategies to enhance the resilience of their formulations.

Automated formulation software is commonly used to optimize ingredient mixes while minimizing costs, but these tools often fail to predict extrusion outcomes based on ingredient properties.

5.6. PROCESS INSTABILITY

Extrusion process instability can arise from various factors, including ingredient-related issues and operational conditions, which can compromise feed quality and production efficiency.

Continuous improvement processes are strongly recommended to minimize these instabilities and achieve better overall control over the production process.

5.7. WASTE MANAGEMENT

There is limited published information on waste generation in feed milling environments, yet minimizing waste is crucial for economic and sustainability benefits. While extruded pellets can be uniform, leading to minimal waste, chips and fines are common and can be recycled into subsequent production.

Production teams are encouraged to control startup and shutdown waste, as excessive waste can lead to financial losses. Downgraded products may be sold at reduced rates or re-worked into future production cycles, but care must be taken to avoid contamination and ensure product conformity.

6. OPPORTUNITIES FOR AQUAFEED EXTRUSION

6.1 PREDICTIVE CHARACTERISATION WITH NIRS

Near-infrared spectroscopy (NIRS) has evolved since the 1960s, finding applications in various fields, including aquaculture. It allows for the rapid, non-destructive analysis of feed ingredients and extruded aquafeed composition. Research by Bourne et al. demonstrated NIRS's effectiveness in predicting proximate composition and starch cook degree across different aquatic species, achieving high accuracy (R^2 values between 0.88–0.97).

Further studies, such as Simon et al. (2022), explored NIRS's ability to estimate the apparent digestibility of nutrients in diets for yellowtail kingfish, revealing significant variability based on ingredient types. This method offers time and cost savings while minimizing animal experimentation, making it a valuable tool for optimizing aquaculture feed formulations.

6.2 EXTRUSION BENEFITS ON GUT FUNCTION

Research indicates a strong link between gastrointestinal microbiota and physiological functions in aquatic species. Factors such as developmental stage, diet, and health status significantly influence microbiota composition. Studies have shown that extruded feed enhances gut microbiota diversity and reduces undesirable microbial species, leading to improved growth performance.

The extrusion process increases starch digestibility and pellet durability, which are crucial for nutrient retention. Future research should focus on how extrusion affects microbial ecology and feed digestibility, potentially leading to formulations that optimize nutrition and promote beneficial microbial profiles.

6.3 PROTECTION OF HEAT- AND SHEAR-SENSITIVE INGREDIENTS

The demand for functional feeds in aquaculture is steadily rising, but extrusion processing can significantly compromise the stability of sensitive ingredients such as vitamins. Encapsulation is increasingly emerging as a viable solution to protect these valuable components during extrusion, although it can be relatively costly.

Alternative methods include post-extrusion applications and the addition of overages of sensitive ingredients before processing. Cold extrusion is another option that preserves nutritional quality but may reduce water stability. Each method presents trade-offs between ingredient integrity and production costs.

6.4 EXTRUSION MODELLING6.4 EXTRUSION MODELLING

Extrusion outcomes are influenced by a variety of factors, and response surface methodology (RSM) is a widely recognized statistical technique specifically aimed at optimizing these complex processes. RSM involves systematically varying independent variables to measure dependent variables, ultimately generating mathematical models that help visualize and predict the intricate and often non-linear relationships between them.

This predictive capability allows for the optimization of extrusion conditions tailored to specific product attributes, enhancing the quality of aquafeed formulations. The advancements in aquafeed extrusion technologies, particularly through NIRS, gut function optimization, ingredient protection, and modeling techniques, present significant opportunities for improving aquaculture feed efficiency and aquatic species health.

6.5. AI- DRIVEN QUALITY CONTROL IN AQUAFEED MANUFACTURING

AI is beginning to revolutionise many industries, including aquaculture, and the integration of AI into aquafeed manufacturing is poised to revolutionize the industry by enabling real-time adjustments and improving efficiency, consistency, and quality of feed production
The extrusion process in aquafeed manufacturing is characterized by its complexity and interdependency, making process control and product optimization challenging for manufacturers. This complexity is exacerbated by the varying feed requirements for different aquatic species and the inconsistent availability and pricing of feed ingredients, necessitating real-time adjustments in operations. The opportunity lies in leveraging AI to manage these fluctuations without incurring high costs or lengthy optimization processes.

AI is transforming various sectors, including aquaculture, and holds promise for addressing the challenges faced in aquafeed production. By combining real-time data analytics with established methodologies, AI systems can surpass traditional sampling and inspection methods. Although AI applications are more advanced in broader aquaculture contexts—such as fish behavior tracking and water quality monitoring—there is a gradual adaptation of this technology for aquafeed manufacturing.
AI systems are proposed to continuously monitor production data and make real-time adjustments to extrusion parameters, enhancing precision, efficiency, and consistency.

By analyzing data from multiple sensors along the production line, AI algorithms can identify anomalies and complex patterns that human operators might miss, facilitating automated defect detection and compliance with nutritional standards. Future advanced systems may include:

- Optimizing ingredient types and ratios for cost-effectiveness and processability.
- Real-time monitoring of critical parameters to ensure high-quality feed output.

- Adapting processing conditions for diverse ingredients, including novel protein sources.
- Predictive maintenance to reduce unplanned downtime by assessing equipment failure risks.
- Minimizing waste and improving throughput by identifying production inefficiencies.
- Non-destructive quality testing of feed pellets using image recognition and spectral analysis.

A notable example of AI in aquafeed manufacturing is FAMSUN's development of AI-driven quality control systems aimed at enhancing extrusion processing efficiency and quality.

Their digital aquatic extrusion systems utilize Industry 4.0 principles, featuring real-time monitoring of critical production parameters to detect deviations and alert operators, thereby minimizing waste and downtime. FAMSUN has also developed multi-parameter regression models to predict feed quality outcomes based on extrusion parameters, stored in a quality prediction model database that assists in determining optimal conditions for new formulations.

Similarly, ANDRITZ's Metris digital platform integrates automation and digitalization to enhance operational efficiency in feed production. Their digital twin technology claims to reduce the need for on-site testing and minimize production losses, while also providing energy savings and operational improvements across various industries. However, independent validation is necessary to confirm the actual benefits of these technologies in real-world feed production environments.

7. THE FUTURE OF AQUAFEED EXTRUSION

The future of aquafeed extrusion research and development lies in addressing the technological, nutritional and sustainability challenges facing the industry, lies in addressing ingredient variability, operational complexity, and sustainability while leveraging emerging technologies such as AI, NIRS, and encapsulation.

Collaboration between industry, academia, and research institutions will be essential to meet the needs of a growing aquaculture sector will be crucial in driving innovation and ensuring the continued growth of sustainable aquaculture.

8. CONCLUSION

Aquafeed extrusion plays a vital role in contemporary aquaculture, offering several notable benefits when compared to traditional pelletization methods, such as improved nutrient retention, enhanced feed efficiency, and a significantly reduced overall environmental impact.

Despite these advantages, the extrusion process encounters obstacles including high costs, complexity, and variability in ingredients. By adopting new technologies and sustainable methods, the aquaculture sector can address these challenges and fully harness the benefits of extrusion technology.

Source : The State-of-the-Art of Aquafeed Extrusion: Mechanisms, Challenges and Opportunities. Jordan Pennells, Michael Salini, Artur Rombenso, Cedric Simon, Danyang Ying. Reviews in Aquaculture. Volume17, Issue2 .March 2025. e70002. https://doi.org/10.1111/raq.70002

TECHNOLOGICAL ADVANCEMENTS IN AQUACULTURE WATER QUALITY MONITORING

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Aquaculture has emerged as one of the rapidly growing industries, creating employment opportunities and providing nutrition to a vast majority of the population.

With the increase in population, the demand for aquaculture has also increased. The usage of information and communication technology in aquaculture helps maintain the quality standards of fish farms which leads to high production, and thus optimizing the cost for the farmers.

However, numerous devices are currently being developed to provide costeffective systems to manage data and water quality. This review aimed to provide an overview of the current aquaculture practices based upon the usage of advanced technology depicting their contribution to aquaculture.

INTRODUCTION

Aquaculture is the world's fastest-growing food-producing sector. It already provides 50% of all fish consumed globally, and is expected to become the primary source of fish by 2030. Despite its growth, some issues such as disease, low production, high input cost, and environmental challenges are affecting aquaculture. Water quality decides whether an aquaculture project will succeed or fail as all the activities of fishes are completely dependent on it as they need to breathe, feed, grow, expel wastes, maintain a salt balance, reproduce and thrive in water.

It is important to understand the physical and chemical properties of water as it is vital to the success of aquaculture to increase production and to avoid risks of environmental damage (Swann, 1997). The continuous monitoring of water should be done so that unfavorable conditions can be predicted in the early stage and can be mitigated (Ferreira et al., 2011).
Fish farming can be carried out in three ways, i.e., extensive, intensive, and semi-intensive (Fig. 1).

Extensive fish farming or traditional fish farming is commonly associated with fish farming in medium- to large-sized ponds or water bodies, where the fish output is based on the water's inherent productivity, which is only little or moderately boosted.

Inputs from outside sources are restricted, and the amount of fish produced per unit area is poor. The level of control over the production components is kept low, but the labor return is high. Intensive fish farming, on the other hand, means that a large number of fish are produced per unit of rearing area.

Production parameters including feed, water quality, and the quality of stocked fingerlings are all regulated to improve the culture's production circumstances. In intensive aquaculture, the risk of disease also increased more due to stocking.

Apart from these two types of fish farming, some people practice semi-intensive fish farming, which refers to techniques that combine aspects of both types.

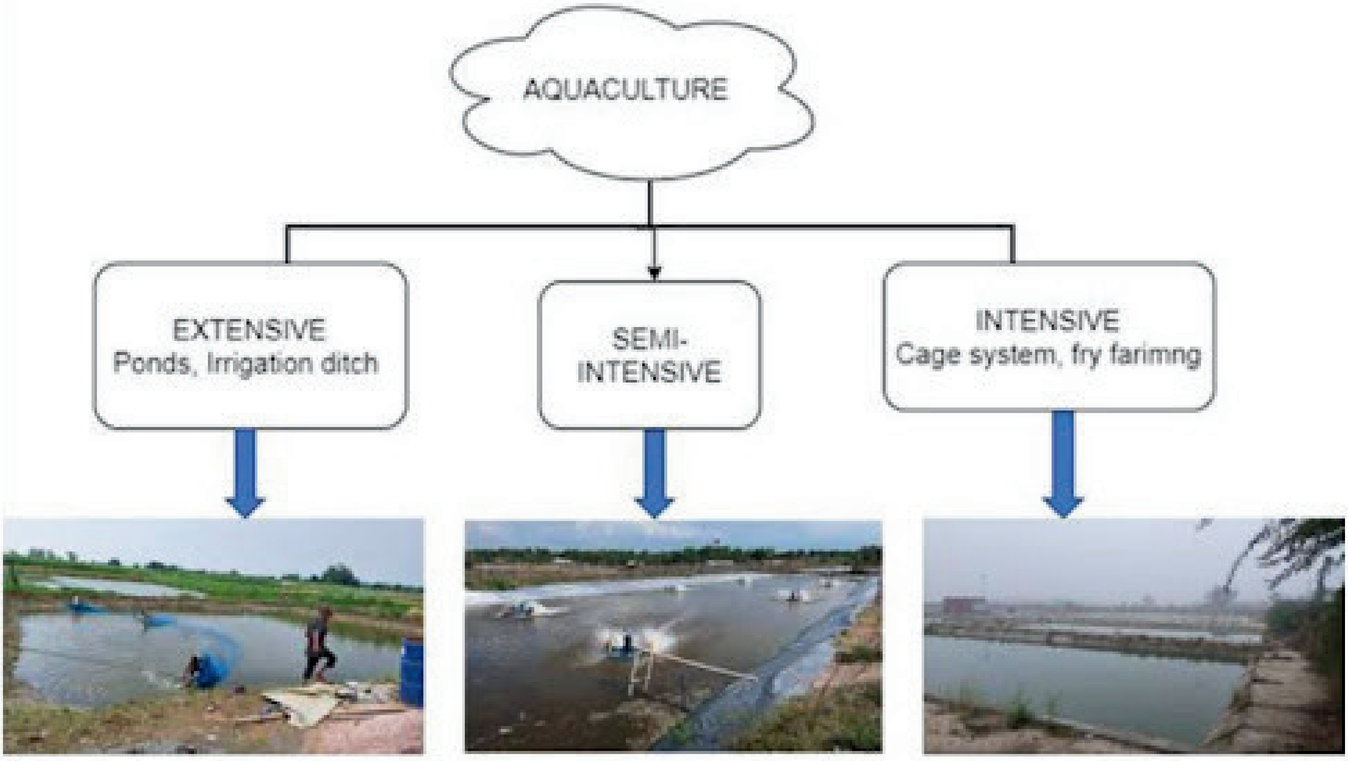


Fig. 1. Types of aquaculture techniques

It can be seen that all methods need extra efforts by farmers to make fish farming their primary economic source. Fish production can be influenced by a variety of factors, including temperature, transparency, turbidity, carbon dioxide, pH, alkalinity, hardness, ammonia, nitrite, nitrate, primary productivity, biochemical oxygen demand (BOD), and plankton population (Verma et al., 2022).

Waterbodies especially near industrial areas get easily contaminated. Due to a lack of environmental regulations and industrialization, these parameters get changed affecting the productivity of the water body. Water temperature mainly affects the growth of aquatic organisms. Massive changes in water temperature result in poor growth.

Fish are cold-blooded, yet their body temperature changes in reaction to their environment. This affects their metabolism, physiology, and production.

As temperature rises, the microbiota's metabolic activity and respiration rate increase to meet the increased oxygen demand. It also lowers oxygen solubility and raises ammonia levels in water. Ammonia is a byproduct of fish protein metabolism and bacterial decomposition of organic substances, including food waste, faeces, dead plankton, and sewage. The unionized form of ammonia (NH3) is highly hazardous, but the ionized form (NH4+) is not. Both forms are collectively referred to as "total ammonia".

A biological process called nitrification can convert toxic ammonia to harmless nitrates. High densities of fish in ponds can increase the risk of ammonia toxicity. Ammonia levels above 0.02ppm can damage gills, destroy mucous-producing membranes, and have "sub-lethal" effects such as reduced growth, poor feed conversion, and disease resistance even at lower concentrations. It can also cause osmoregulatory imbalance and kidney failure.

However, toxic levels of nitrite, an intermediate form of ammonia, have been observed in fish ponds causing brown-blood disease (Bhatnagar et al., 2013).

As phosphorus is a necessary plant nutrient, adding it to water will encourage the growth of plants, including algae. According to Stone and Thomforde (2004), a phosphate level of 0.06mg L-1 is desirable for fish culture. Dissolved gases, particularly nitrogen, are typically measured in terms of "percent saturation." Supersaturation occurs when the amount of gas in the water exceeds its typical capacity at a specific temperature. Gas supersaturation levels above 110 percent are often considered harmful. Gas bubble illness is a sign of gas oversaturation. The symptoms of gas bubble sickness differ. Bubbles can reach the heart or brain of fish, causing them to die without an obvious evidence. Other symptoms may include bubbles beneath the epidermis, in the eyes, or between the fin rays. To treat gas bubble disease, aeration should be adequate to reduce gas concentrations to saturation or below (Swann, 1997).

The acidity or basicity of water is determined by the concentration of hydrogen ions (H+) in it. The pH scale, which goes from 1 to 14, is used to determine how acidic a substance is. Values below 7 are regarded as acidic, while values above 7 as basic. A value of 7 is neutral, neither acidic nor basic. According to Swann (1997), for fish culture, a pH range of 6.5 to 9.0, is usually appropriate. Low pH results in acidic water due to the leaching of metals from rocks and sediments occur. This results in the fatality of fish as these further accumulate in organs. Numerous data points show that fish metal accumulation rates are directly impacted by water acidification. When data on metal concentrations in fish from different lakes are compared, it can be seen that fish from acidified lakes have significantly higher concentrations of cadmium and lead, but not zinc (Grieb et al., 1990; Wiener et al., 1990; Haines & Brumbaugh, 1994; Horwitz et al., 1995). Copper accumulation is likewise greater at lower pH values (Cogun & Kargin, 2004). In summary, water acidification may either directly or indirectly affect fish bioaccumulation of metals by altering the solubility of metal compounds or by damaging epithelia that become more permeable to metals whereas in some cases competitive uptake of H+ ions may prevent fish bioaccumulation of metals (Jezierska & Witeska, 2006).

With the increasing trend of intensive aquaculture, threat of disease has increased, which should be tracked and regularly monitored. All of these measures necessitate strong procedures and investments, raising production costs.

Many methods are used to monitor water quality, but they either serve purposes other than aquaculture or lack integration with online communication systems.

The conventional method (Fig. 2) in which first the samples are collected from the site and are then transferred to the laboratory for the test. .

These are time-consuming and also there are chances of large variation as work may vary from person to person based on their previous experience (Zhu et al., 2010)

As the reliability of technology increased, the focus on implementing it in every field has also increased.

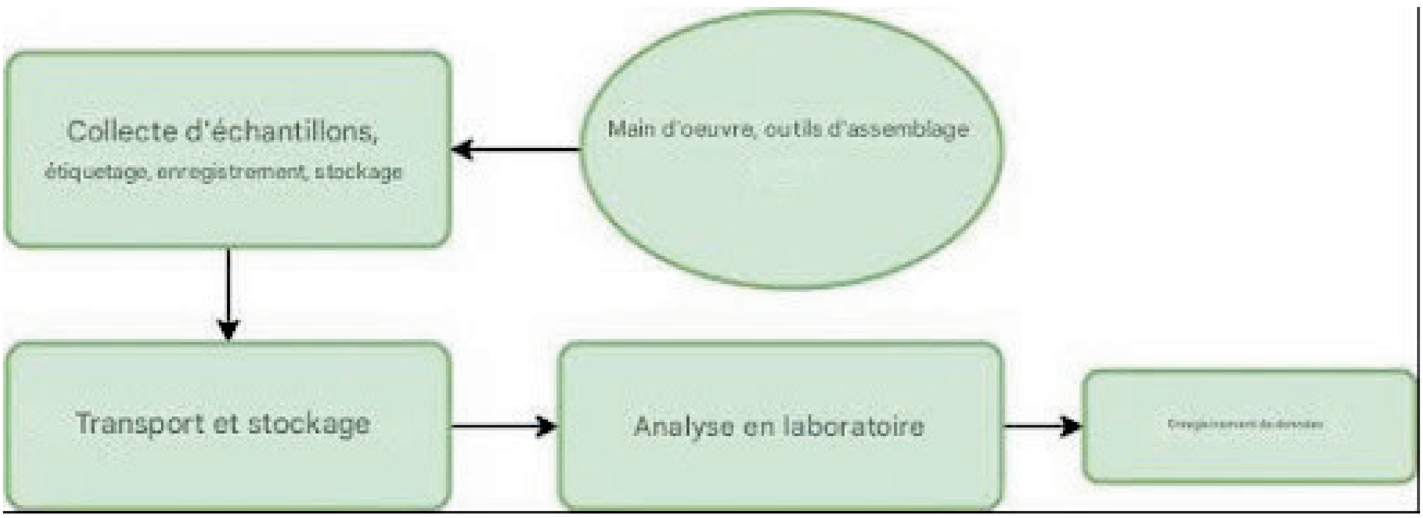


Fig. 2. Conventional water quality assessment procedures for aquaculture monitoring

Fish farming has the least exposure to technology due to which its productivity suffers and therefore the involvement of technology is necessary for this area. Technology in aquaculture can help increase productivity. With the help of technology, farmers can easily keep track of their work with fewer efforts (Powell et al., 2017). For the monitoring of water quality in aquaculture, there are countless methods proposed in this area.

But not all are equally beneficial, some are time taking while some are costly or not conveniently available to the small farmers. Water quality monitoring systems based on wireless communication technologies (WCTs) and the Internet of Things (IoT) have been widely studied around the world (Danh et al., 2020). In this review, we focused on some of the technologies which are currently used in the aquaculture field to monitor water quality.

SENSORS AND WIRELESS TECHNOLOGY FOR AQUACULTURE MONITORING

Physical (electrical conductivity, salinity, total dissolved solids, turbidity, temperature, color, and taste and odor) and chemical water (pH, acidity, alkalinity, hardness, chlorine, and dissolved oxygen) quality parameters are some of the important variables which play a pivotal role in affecting the water quality.

Previously, several technologies were used for water quality monitoring but they were not connected with online monitoring systems. Traditionally, the water quality of fish farms was tested on-site using handheld sensors (Fig. 3) on a regular basis.

Regardless of the species of fish, the aforementioned physical requirements are typically necessary to sustain optimal levels of fish growth.

Fig. 3. Different types of handheld sensors for testing aquaculture physiochemical parameters. (A) Conductivity/TDS meter, (B) Digital nephlo-turbidity meter, (C) pH meter, and (D) Scientific thermometer.

While handheld tools or sensors can offer onsite measurement by staff during office hours, variations in one of the essential water parameters beyond a safe threshold can occur outside of office hours, undetected by employees. When a terrible condition persists, it might have negative consequences such as low growth, undiagnosed disease symptoms, or strange fish behavior.

However, real-time monitoring based on wireless sensor networks (WSNs) makes the monitoring much more convenient and accurate (Zhang et al., 2013). WSNs are a type of network that consists of interconnected sensor nodes that communicate wirelessly in order to collect data about the environment.

The use of technology in monitoring has been introduced/ picked in the last decade. A remote wireless system was introduced by Zhu et al. (2010) using wireless communication technology for online water quality monitoring in intensive fish culture.

This system monitors dissolved oxygen (DO), pH, salinity and temperature in real-time and gave more than 95.2% correct data. It can also give early warning signals on notable changes in values. The proposed system's application is however currently limited due to its rigorous operational requirements and expensive maintenance costs.
Water quality monitoring systems for aquaculture based on wireless sensor networks have sensors that monitor pH, water level, DO, and temperature. This system senses these parameters in real-time and also send the data directly to the users. It is user friendly, as it can monitor the data at any time on demand. This along with wireless sensors equipped with decision-making control software which make use of expert knowledge stored in the database can achieve better results (Zhang & Wang, 2011).

In a further development, a wireless system to monitor some basic and important parameters of water quality such as DO, pH, conductivity and temperature was developed with a wireless communication interface that communicates to the remote station located around 1km area of the interested site. The system was found to withstand harsh environmental conditions but was found to be not economically feasible (Vaddadi et al., 2012). On the other hand, the ZigBee wireless sensor network-based water monitoring system can store the sensor values and compare them with the reference limits. It monitors all the common parameters temperature, pressure, DO and can send an alert via SMS or E-mail to the holder if the values exceed the reference limits (Espinosa-Faller & Rendón-Rodríguez, 2012).

Recently, Chen et al. (2022) in Taiwan developed a robotic arm performing automatic measurements and maintenance procedures. The Arduino Mega 2560 microcontroller was used to transmit the water quality dataset over a LoRaWAN networK.

INTERNET OF THINGS (IOT) SOLVING ECONOMIC ISSUES

The internet has evolved enormously over the last four decades, from a small private network of a few nodes to a global public network with billions of nodes. The term "Internet of Things" (IoT) was coined by Ashton (1999) to describe the trend toward networked "things" that collect data through sensing and execute calculations on the sensor data.

IoT is a broad word with no clear meaning, but it refers to a wide range of "things," from everyday objects to complicated biosensors, that are capable of sensing/ actuation, communicating to the internet, and processing. The IoT is the concept of connecting any device to the internet and other connected gadgets (Fig. 4).

The IoT is a huge network of networked objects and people that collect and share data on how they are used and how they interact with their surroundings.

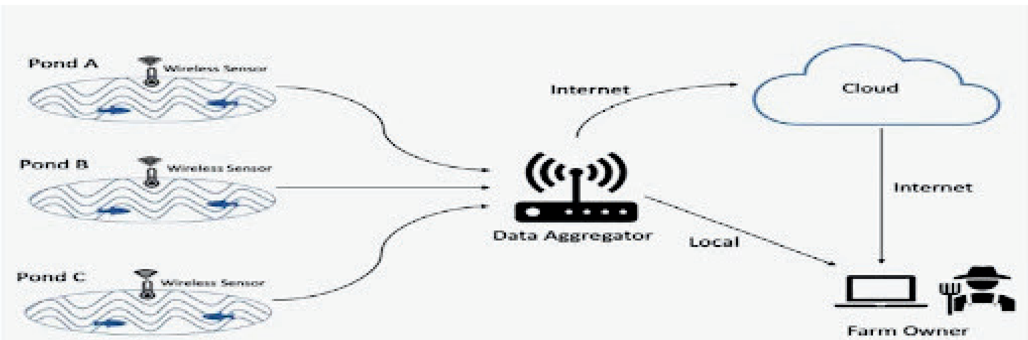


Fig. 4. Implementation of wireless IoT communication technology in fish farm management

In implementing the different systems for ensuring the quality of fish farms, the main barrier is high cost. Small farmers in comparison to large farmers lack the advanced technology system for to check the progress of their work. Also hiring people to work on daily water quality checks is not possible for small farmers (Teja et al., 2020). The aquaculture IoT systems are economically very useful. The farms which are using IoT systems are more productive than those that are not using them; as IoT systems decrease the labor cost and are less time taking. Sung et al. (2014) proposed a wireless remote monitoring system using the wireless sensor network with the ZigBee which monitored the temperature, pH and DO on aquaculture farms. The system enables real-time monitoring with the aid of mobile devices and remote platforms. The system collects the data with the date and time and sends the information to the internet from which the information can be accessed easily and helps control the situations of farms.

A cost-effective and multiparameter monitoring system was developed which provides real-time data on aquaculture water quality based on a wireless sensor network (Luo et al., 2015). The system uses lithium cells and solar cells for the power supply and has sensors for DO, ammonia, nitrogen, temperature and pH. However, the system lacked automatic control of pH, ammonia, nitrogen and needed further improvement. Powell et al. (2017) gave a scalable, versatile, more economical remote monitoring system with the concept of IoT and proposed its future work with artificial intelligence (AI) in the system for more advantageous results. The system was designed to monitor the temperature, pH, DO and stored the data provided by the sensors in a database easily accessible from anywhere through the mobile app.

With the increase in developing better products, Gao et al. (2019) developed an IoT-based intelligent fish farming and tracking control system. The system not only performed monitoring of the parameters of water quality but also was able to keep track of breeding as well as the sale of fish. The system includes six types of sensor monitors for simultaneous measurements of temperature, conductivity, water level, pH, water turbidity and DO. The collected data from the sensors get stored in a database system. The system also included a product tracking system in which by scanning the QR code of the product, one could trace all the information regarding the product such as its geographical location, transportation and all the farming process to the consumer. This system is a highly useful improvised approach, as the system could prove very effective in providing the trustworthy quality of aquatic products. Boonsong et al. (2018) suggested a wireless sensor network (WSN) in an IoT platform for a smart water quality monitoring (SWQM) system of aquaculture ponds. Temperature, the amount of dissolved oxygen in water, and potential hydrogen (pH) values were the key variables examined in this study. The router gateway transmits the data that is monitored with the suggested SWQM device to an operator via a cloud Internet platform. To accomplish real-time monitoring, the operator can use the tracked information data on a smart device.

In another recent report, a low-cost sensor to monitor pH, temperature, water level and humidity was developed (Teja et al. 2020), which stores data at regular intervals of time in the cloud and is accessible by the user through the Blynk application in their mobile. The system can send alerts to the user and can take important actions automatically.

SMART AQUACULTURE

There is a consistent requirement for intensified aquaculture production to meet the food demand of the growing global population. Given the diversity in aquaculture farming in terms of methods, practices, and facilities, human labor alone is insufficient and new intelligent aquaculture models are greatly needed (Wang et al., 2021).

The emergence of the IoT, big data, artificial intelligence, 5G networks, cloud computing, and robot technologies makes intelligent aquaculture possible (Li & Li, 2020). Intelligent aquaculture can increase resource usage efficiency and sustainability in a variety of ways. It can also lower labor costs, boost production, and improve aquatic product quality.

Other problems, such as high capital and energy costs, should, however, be addressed in order to develop intelligent aquaculture (Li & Li, 2020). Recently, keeping in view the concept of smart aquaculture, Sivakumar and Ramya (2021) proposed a system named as low-cost real-time monitoring system (LCRTMS). This system with IoT monitors pH, water temperature, DO and ammonia. Sensors collect the data and send it to the cloud over the internet which can easily be accessed and the further process can be done with minimal human interaction. Akhter et al. (2021) proposed a low cost, low power water quality monitoring system with IoT based sensors to access the data in real-time. The system has multi-sensors to monitor various parameters which include temperature, pH, DO, calcium, magnesium, nitrate and phosphate. The proposed system can be easily operated to keep track of the water quality regularly. Additionally, the users can get expert advice from anywhere anytime they need.

Lin et al. (2021) proposed a novel wireless multi-sensor system that monitors the water quality of freshwater aquaculture by combining the temperature, pH, DO, and EC sensors with an ESP 32 Wi-Fi module. The ThingSpeak IoT platform presented the temperature, pH, DO, EC, and salinity levels of the water along with an easy-to-use visualization provided by the ThingView APP. The suggested wireless multi-sensor IoT system is capable of monitoring freshwater aquaculture water quality with adequate accuracy, dependable confidence, and good tolerance.

In terms of smart aquaculture, the suggested wire-free multi-sensor IoT system has several advantages over multiple single sensors, including easier setup and maintenance, better cost-effectiveness, and sufficient accuracy and reliability with pre-calibration even for commercialized sensor devices. Additionally, the system allows for simultaneous on-site monitoring of multiple sensing parameters in close proximity to an aquatic cultivation field over weeks or even months, as well as a significantly cost-effective improvement in labor costs.

Another system named E-Sensor AQUA system is a water quality monitoring IoT based system useful in measuring the pH, salinity, temperature, oxidation-reduction level, and DO in real-time. The system also has an automatic sensor probe cleaning mechanism which reduces the high maintenance cost and makes use of technology affordable to small farmers. All of these systems were designed to meet the demand for multimode sensors by establishing data communication and a feedback loop to initiate actions. To ensure data reliability, a reliable sensor network should have optimal sampling algorithms continuing with the aim of smart aquaculture. In most cases, IoT solutions in aquaculture employ a local server to store the massive amounts of data collected in an Excel file or database. As a result, the Internet infrastructure is put under a lot of strain. Cloud computing supports IoT by providing a virtual storage location and conduit for the massive amounts of data and applications that need to be stored and retrieved. It not only improves the approaches' efficiency and scalability, but it also enables improved collaboration between engineers working from different locations (Gupta et al., 2022).

The latest example of an intelligent fish farm is the one designed by Chiu et al. (2022) to meet the requirements of a California Bass fish pond in Taiwan. Their primary objective is to streamline the manpower needed for fish pond maintenance through the utilization of automated devices and Artificial Intelligence of Things (AIoT). The proposed intelligent fish pond incorporates various sensors, including dissolved oxygen, pH, turbidity, and temperature sensors. Devices such as the heater, water pump, and pH sensor are shielded by a wind-proofing device during fish pond operation. Others, like the food-feeding device, turbidity sensor, dissolved oxygen sensor, temperature sensor, and agitator, interact directly with the fish pond without wind-proofing protection. A micro-controller, specifically the Arduino Mega2560 with an integrated Wi-Fi module, orchestrates the heater, water pump, limit switch, all sensors, food feeding device, IPCAM, motor, and agitator for real-time surveillance (Chiu et al. 2022). All data are stored in a cloud server, where they are collected and analyzed using big data and AI techniques. Important features are then employed to generate deductions on the system’s productivity through machine learning, including deep learning.

Mobile applications are also available for remote surveillance and control (Chiu et al., 2022). Data from the California Bass fish pond system were collected over fifty-two weeks. Following statistical verification and analysis, the optimized prototype achieved a high R2 value of 0.94, with an average square value of 0.0015 (Chiu et al., 2022). These values demonstrate the feasibility of the proposed model to achieve the desired output. The researchers believe that this intelligent fish pond model can offer significant benefits to fish farmers worldwide, including reduced food residue, enhanced fish growth, minimized fish mortality, and improved feed conversion ratio.

Currently, biosensors, which use electronic technology to evaluate the functions of living organisms, are being actively researched and developed. Biosensors use electrodes and optical devices to detect small changes and convert them into electric signals, allowing for quick and accurate measurement of specific substances. Biosensors with high sensitivity and specificity are being developed for assessing fish health (Endo et al., 2019). Physiological stress in fish causes a primary response of hormone concentration changes, such as cortisol and catecholamine, followed by a secondary response of blood glucose changes due to stress hormone metabolic activation.

The stress response is influenced by physical factors like flow velocity, temperature, and contact, chemical factors like ammonia, nitrous acid, and poisons, and behavioral factors like predation threats, fish social activities, and territorial behavior (Bonga, 1997). While various factors such as high ammonia levels, can cause chemical stress. Endo et al. (2006) created a needle-type biosensor system that consists of an optical oxygen fiber probe with a ruthenium complex, an immobilized enzyme membrane, and a hollow needle-type container (18-gauge needle) for the quick and easy measurement of glucose concentrations in fish blood. This sensor inserted into the caudal vein of the fish, measure blood glucose concentrations by measuring changes in the concentration of dissolved oxygen. This procedure involves removing the fish from the water tank using a net in order to draw blood samples for each measurement, which could stress the fish unnecessarily. Additionally, fish glucose concentrations vary in response to stress, making real-time measurement extremely desirable.

Endo et al. (2010) devised an innovative wireless biosensor system which is inserted in the eyeball interstitial sclera fluid (EISF), the interstitial fluid inside the outer membrane of the fish eyeball to track fish glucose levels in response to these issues.

The output current value of the sensor is transmitted to land via radio waves, allowing the glucose concentration to be tracked in real time by connecting it to a waterproof wireless potentiostat.

This kind of fish sensor system is novel and can measure blood glucose levels in real time even when test fish are swimming around freely. In addition, to be able to assess stress responses using a more intuitive output, Wu et al. (2019) developed a method of visual output an optical communication type biosensor system to indicate the level of stress which can measure blood glucose concentration.

PRECISION FARMING VIA TECHNOLOGICAL INNOVATION

With the challenges mentioned for aquaculture production, various strategies must be identified and implemented. The availability of unmanned vehicles outfitted with overhead cameras, sensors, and computational capability for site surveillance also are well known.

To achieve more precise fish farming, more autonomous and continuous monitoring is required, which can give more reliable decision support and decrease reliance on manual labor and subjective evaluations to improve worker safety and welfare.

Precision aquaculture is defined as a network of heterogeneous and interconnected sensors used to monitor, analyse, interpret, and support farm operations (Teja et al., 2020).

It applies control engineering principles in fish production to improve farm monitoring, control, and allow documentation of biological processes and biomass monitoring (Føre et al., 2018).

Because precision agriculture is developing so well, the suggested IoT platform by Lin et al. (2021) offers a biotechnology development that is both flexible and expandable, enabling the simultaneous monitoring of a wide range of cultivation parameters in agriculture while maintaining transparency and quality control throughout the entire process. Measurement robustness and user-friendliness will be improved upon by taking consideration of the ageing and maintenance needs of aquatic sensors. Because of its availability and affordability, unmanned vehicles or aircraft are one of the developing technologies widely used in agriculture and aquaculture for fish management and monitoring. Drones are now being used to capture environmental data and fish behavior at aquaculture sites for monitoring (Chang et al., 2021; de Lima et al., 2021).

Autonomous underwater vehicles (AUVs) or remotely operated underwater vehicles (ROVs) are waterproof and submersible in water because they are outfitted with cameras to capture images and videos as well as sensors to collect data on water quality such as water temperature, depth level, chemical, biological, and physical properties (Paull et al., 2014; Sward et al., 2019; Yuan et al., 2023). Because AUVs are submerged underwater, one of the problems is high navigational precision, communication, and localization due to the inability to rely on radio communications and global positioning systems. Yet, one of the solutions proposed to address these issues is geophysical navigation (Ubina et al., 2022). An augmented reality (AR) plus cloud system has recently been developed to enhance the query and gathering of in-situ water quality data (Xi et al., 2019; Yue & Shen, 2022). AR is also expected to make significant contributions to fish farm management, such as water quality management, remote collaboration, and boardroom discussion. However, the affordability of such systems is always an important consideration when using this technology on small fish farms. In addition, the aquaculture industry benefits from the development of simple and cost-effective AR software. Testing is being done on a 3D-printed water sensor system that can identify pH, temperature, and oxygen content (Banna et al., 2017).

The cost of manufacturing and equipment, the need for post-processing, and the scarcity of materials suitable for use in water and other environments are some of the obstacles to 3D printing's adoption in aquaculture. Collaboration among aquaculture scientists, fish farmers, engineers, and software developers is necessary to address these issues and create cost-effective products for the aquaculture sector by integrating 3D printing technology into products and business models. The aquaculture sector could undergo a revolution, thanks to IoT and big data solutions, which would increase productivity, sustainability, and profitability while also enhancing safety and simplifying risk management. Consequently, it greatly increases the interconnectedness of supply chains and processing systems. Applying IoT technologies to remote marine aquaculture sites is still a practical challenge, though, as data collected from sensors located far from the main fish farm must be sent elsewhere in the world (Yue & Shen, 2022).

Issues such as high labor cost, time consuming and susceptibility to errors due to traditional methods may get possibly solved through the integration of computer technologies like data analytics, the IoT, and AI. Nevertheless, there are issues with performance, interpretability, and data variability with the deep learning systems available today. To address these limitations, Arepalli and Naik (2024) proposed a comprehensive framework that incorporates IoT-based data collection and data segregation techniques to improve the precision of aquaculture water contamination classification. The study introduced the Ordinary Differential Equation Gated Recurrent Unit (AODEGRU), a novel attention-based model to assure robust categorization. Accurate classification of water contamination and water quality evaluation is enabled by utilizing advanced device sensors enabled real-time data collection for temperature, pH, dissolved oxygen, and nitrate concentration. This AODEGRU model computes a water contamination index using fish-specific permissible ranges, which makes it easier to accurately separate data into contaminated and non-contaminated classes as this model is trained with labelled, high-quality data. Even so, it has limitations in terms of adjusting to aquaculture's dynamic character.

However, the study further focused more on factors in future research like scalability, long-term maintenance, and flexibility to changing circumstances. Although sensors make things smooth, using them comes up with many challenges. Sensors must be low-maintenance, low-cost, battery-efficient, robust, waterproof, non-metallic, biofouling-resistant, and non-toxic to organisms. If possible, it is recommended to avoid using optical sensors. It is important to study the threshold values of fishes' hearing abilities and the effects of magnetic fields caused by sensors (Parra et al., 2018).

In addition, concerns about data security and privacy arise when IoT is implemented in numerous businesses, and aquaculture is no exception. The aquaculture sector contains a lot of sensitive data, including trade secrets and patented techniques, which makes protecting these data an essential issue (Assaf et al., 2024). In general, aquaculture has benefited from IoT-based technologies since it makes real-time management easier while enhancing sensor corrosion resistance and incorporating data fusion to improve decision-making require improvements (Abdullah et al., 2024).

CONCLUSION

It is evident from the data that aquaculture is a rapidly growing and in-demand sector of farming. Until now, most farmers have relied on traditional fish farming methods, which have resulted in low efficiency and yield. These challenges can be overcome through the use of technology, enabling farmers to monitor and manage water quality while saving labor costs and time, ultimately improving fish production. To meet growing demand, aquaculture must adopt these technologies at the same, or even a faster, pace.

The evolution of sensors and IoT implementation in aquaculture has elevated fish farming to new levels, but it has not penetrated the industry as expected. There are significant gaps between the availability of revolutionary and disruptive technologies and their actual usage in aquaculture. Barriers such as high costs, low-level implementation, limited customization (according to farmers' needs), and the complexity of understanding these technologies prevent widespread adoption among fish farmers.

IoT in aquaculture offers new hopes for increased productivity, but it requires improvement. Moving forward, the focus should be on developing technology that is easy to understand, simple to implement, efficient, and affordable—features that will drive large-scale adoption among Fish farmers.

SUSTAINABLE AQUACULTURE PRODUCTION FOR IMPROVED FOOD SECURITY

By Kwasi Adu Obirikorang. Department of Fisheries and Watershed Management, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana

Food security has been persistently recognized in global discourse as one of the world's main challenges. Despite some progress toward ensuring access to safe, nutritious, and sufficient food for all people year-round (SDG Target 2.1) or eradicating all forms of malnutrition (SDG Target 2.2), FAO et al. (2024) estimated that between 713 to 757 million individuals (8.9%-9.4% of the worldwide population) experienced undernourishment in 2023. Based on the mid-range figure of 733 million, about 152 million additional people may have faced hunger in 2023 compared to 2019. With outputs from capture fisheries stagnating over the past few decades, aquaculture holds the potential to play crucial roles in achieving food security (FAO, 2020). Global demands for fish are expected to increase in future decades to meet the needs and preferences of a growing human population (Jennings et al., 2016). With global populations projected to increase to over 9.7 billion by 2050 (United Nations, 2024), seafood in general and fish in particular will continue to play an important role in providing nutrition and food security globally, especially in developing countries (Cojocaru et al., 2022; Bjørndal et al., 2024).

Two separate but interconnected sectors contribute to global fish supply: capture or wild-caught fisheries and aquaculture or farmed fish. In fact, as capture fisheries have leveled off, continued increases in production from aquaculture will be required in order to maintain or increase per capita fish consumption (FAO, 2020).

According to the FAO (2022), aquaculture has for several decades, been the fastest growing animal production sector in the world, contributing to 49% of total aquatic production (FAO, 2022). This rate of growth and the sector's contribution to global food security, however, appear to be much lesser than estimated when seaweeds (algal autotrophs) are excluded from the production statistics and comparisons to terrestrial livestock productions are made based on only edible yields (Edwards et al., 2019). This, notwithstanding, the sector still holds the potential to make important contributions to sustainable food futures although its rapid expansion has consequences relating to environmental sustainability. Additionally, the sector faces challenges relating to the high cost of aquafeeds for finfish and shellfish, post-harvest losses, and pathogen-induced mortalities.

The article submissions to this Research Topic make contributions to solving some of the problems the aquaculture sector faces through perspectives, reviews, and original research works focusing on various aspects of aquaculture, including sustainable production (Chen et al.; Shen et al.; Mizuta; N'Souvi et al.), aquaculture nutrition (Akter et al.; Andam et al.), postharvest processing technologies (Barros et al.), production systems (Rossignoli et al.), fish health and welfare (Stentiford et al.; Zornu, Tavornpanich, Brun, et al.; Zornu, Tavornpanich, Shimaa, et al.), and aquaculture finance (Munguti et al.).

The primary data for the articles published under this Research Topic were sourced from 13 countries spread across three continents and broadly fall under the three pillars of sustainability:

Environmental sustainability (production technologies that optimize fish production and/or minimize significant environmental disruptions or impacts).

Economic sustainability (private-public sector partnerships and multinational donor investments).

And social and community sustainability (social dimensions of aquaculture, especially in developing countries).

The development of aquaculture hinges largely on the formulation and production of low-cost, but nutritionally balanced aquafeeds for finfish and shellfish culture, but aquafeed remains prohibitively expensive for many small-scale farmers. The aquafeed industry has long depended on fishmeal as a chief protein source, but unstable supplies and erratic price fluctuations have called for partial or total replacements with more sustainable raw materials (Roques et al., 2020). The studies by Akter et al. and Andam et al. thus highlight the advancements in aquaculture nutrition over the last two decades through continuous innovations in feed formulation to improve feed efficiency and sustainability. The replacement of fishmeal with mysid meal up to 65% in diets for the Pacific white shrimp (Penaeus vannamei) without negatively impacting growth performance, feed utilization efficiency, and body composition (Andam et al.) represents a cost-saving strategy that can increase the profitability of shrimp culture.

The successful inclusions of mustard oil cake, soybean meal, and rice bran as fishmeal replacers in diets for Labeo rohita (Akter et al.) highlight the possibility of using these unconventional ingredients as dietary protein sources to minimize fish production costs and positively contribute to increased food security, particularly in developing countries.

Due to significant pathogen-induced mortalities, aquaculture, which provides half of the world's aquatic protein, faces difficulties in providing a safe and sustainable fish supply. Investigating the causes of fish mortalities (Zornu, Tavornpanich, Brun, et al.), extending the interpretations of diseases beyond the identification of disease agents to address host, environmental, and human factors (Stentiford et al.), and bridging knowledge gaps in fish health management through education and research (Zornu, Tavornpanich, Shimaa, et al.) can enhance aquatic animal health and foster a resilient and sustainable aquaculture industry.

Sustainability in aquaculture development is further gaining prominence due to environmental issues like water pollution.

Reducing the impacts of aquaculture production on the environment should be a key focus if the sector, which paradoxically is largely dependent on clean water, is to sustainably contribute to global food and nutrition security. The implementations of resource-efficient and environmentallyfriendly approaches such as green total factor productivity (the efficiency of aquaculture production considering environmental sustainability) (Shen et al.) and the adoption of emerging green production technologies in production (Chen et al.) are key ways to ensure this. To build resilience and sustain production in the face of climate change and environmental degradation, aquaculture producers must adapt to short-term available options such as shading ponds and aeration or make long-term adjustments to production practices, including diversifying production systems and areas (Maulu et al., 2021). By expanding the areas available for aquaculture production, the industry can significantly increase its overall production capacity, enabling it to better meet the growing human demands for fish and other aquatic products across the world.

Aquaculture production in inland saline environments, also known as "desert aquaculture" in some jurisdictions, offers the potential to increase production of euryhaline and marine species. While commercial aquaculture production using saline groundwater is well-developed in countries such as the USA, Israel, India, and Australia (Allan et al., 2009), it remains underdeveloped in some developing countries such as Pakistan (Rossignoli et al.). Inland saline waters provide key resources for producing fish and other aquaculture products by employing otherwise unproductive resources while minimizing reliance on freshwater resources, which otherwise serve as potable water sources for humans. The study by Rossignoli et al. serves as key baseline data to address some of the information gaps crucial for the sustainable development of saline aquaculture in developing countries. There is the need to strengthen technical skills in saline aquaculture in tandem with the establishment of hatcheries for salttolerant species, aiming to reduce dependence on freshwater species in saline pond environments.

With several projections highlighting the vulnerability of the entire aquaculture value chain to climate change and environmental degradation, there are valid concerns about whether the sector is growing sustainably and fast enough to meet future demands, further exacerbated by the rapidly growing human population. The present shifts in human dietary patterns toward sustainable foods may further cause the demand for seafood to rise sharply over the next 10 years, necessitating further research on innovative aquafeeds in all areas of sustainability.

Prioritizing research on low-cost and complementary ingredients in aquafeeds, especially for species in low-trophic production systems, will be an innovative way to stimulate the development of the sector. Additionally, there is the need to adopt innovative production methods, prioritize disease prevention measures, and minimize the environmental impacts to optimize the economic, social, and environmental efficiency of the aquaculture sector.

TRANSFORMING SOUTHERN AFRICA'S FUTURE WITH INTEGRATED MULTI-TROPHIC AQUACULTURE

By: Tafadzwa Maredza. Fisheries Officer, Ministry of Lands, Agriculture, Fisheries, Water and Rural Development, Zimbabwe.

The global demand for fish and fishery products is steadily increasing, largely due to the sector's role in reducing poverty and enhancing food security. In developing countries, particularly in the Southern African region, fisheries and aquaculture are crucial for providing food and income. These industries are often integrated with other agricultural activities, such as crop farming and livestock rearing, and they significantly contribute to boosting rural economies as economic multipliers. However, there is a growing global movement toward identifying alternative and sustainable strategies to mitigate the overexploitation of wild fish stocks. To address the decline in fish supplies from capture fisheries and meet the rising global food demand, the aquaculture industry has experienced rapid growth. As a result, aquaculture has now surpassed capture fisheries.

In 2022, global aquaculture production reached a record 130.9 million tonnes, accounting for 59% of total fisheries and aquaculture production, valued at USD 312.8 billion (FAO, 2024).

The stand-alone mono-species operations commonly found in traditional aquaculture can pose significant environmental challenges, often harming the ecosystem without directly benefiting local communities. Therefore, there is a pressing need to innovate and develop environmentally friendly and economically viable aquaculture systems. Integrated Multi-Trophic Aquaculture (IMTA) systems were created in response to this need.

In many IMTA initiatives, co-cultured species work together to produce multiple resources without requiring additional inputs such as feed or seed, and they do not create problems related to increased effluent. This article explores the potential of the IMTA concept to promote sustainable environmental protection and aquaculture development in Southern Africa.

In the next article, we will discuss the inherent challenges and bottlenecks associated with implementing IMTA in the region and suggest practical solutions to address these issues.

WHAT DOES INTEGRATED MULTI-TROPHIC AQUACULTURE (IMTA) MEAN?

This terminology can be understood by breaking it down into its component words. Most of us recall that a food chain represents the energy pathway in a community, transferring food from those who produce it to those who consume it. For instance, plants are eaten by herbivores, which are, in turn, consumed by carnivores.

According to the Merriam-Webster Dictionary, the term "trophic" is derived from the Greek word "trophikos," which comes from "trophē," meaning nourishment. Therefore, a trophic level refers to the different feeding (and thus energy transfer) levels in the food chain, ranging from producers to consumers.

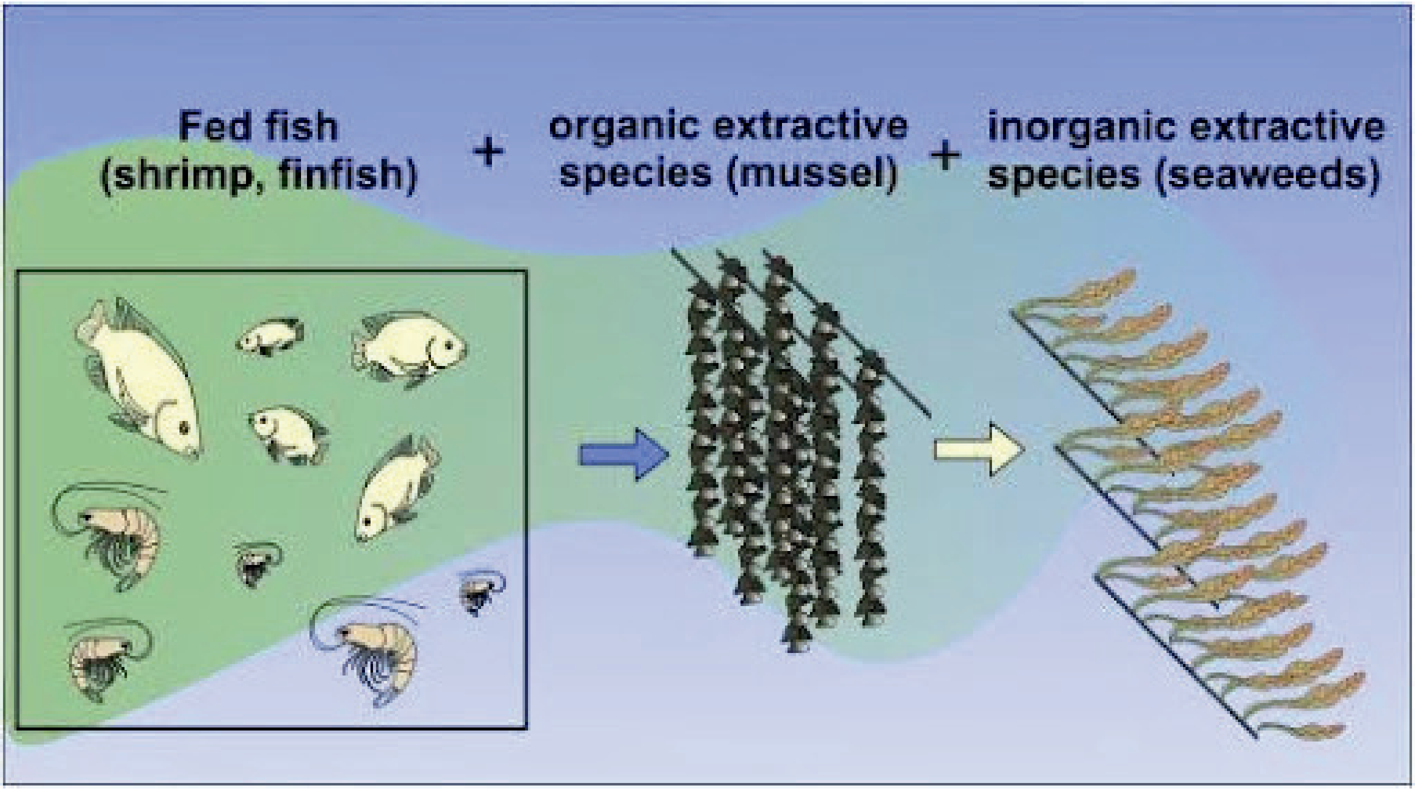
Additionally, the prefix "multi-" means 'more than one' or multiple. Another key term is "integrated," which means 'combined' or 'mixed.'

Consequently, IMTA can be defined as an innovative aquaculture strategy that combines different species from various trophic levels into a single system. This method aims to create a balanced ecosystem where the waste produced by one species serves as a nutrient source for another. IMTA is a sustainable aquaculture strategy that combines different species from various trophic levels to create a balanced ecosystem. In Integrated Multi-Trophic Aquaculture (IMTA), species are categorized into three groups: fed fish, organic extractive species, and inorganic extractive species.

Fed fish, such as salmon and tilapia, receive external feed, and their waste, including uneaten food and faecal matter, supports other species in the system, thus reducing nutrient pollution and enhancing resource efficiency. Organic extractive species, like bivalves (oysters and mussels) and certain macroalgae, obtain nutrients from organic matter in the water; they filter the water and recycle nutrients, improving overall water quality.

In contrast, inorganic extractive species, such as specific macroalgae and duckweed, absorb inorganic nutrients directly from the water, benefiting from the nutrient-rich effluent produced by fed fish, and helping to remove excess nutrients, which promotes a more sustainable aquaculture environment.

IMTA not only enhances biodiversity but also promotes sustainable practices by optimizing resource use and minimizing environmental impacts. As aquaculture continues to grow globally, particularly in developing regions like Southern Africa, IMTA offers a viable solution to the challenges faced in traditional aquaculture systems.



HISTORY OF IMTA

The history of Integrated Multi-Trophic Aquaculture (IMTA) can be traced back to John Ryther, often referred to as the "grandfather of modern IMTA."

In the 1970s, his ground-breaking work on combining waste recycling with marine polyculture systems reignited interest in the concept.

Ryther integrated various existing ideas, such as polyculture, ecologically engineered aquaculture, and the combination of fish and plant cultures, emphasizing the advantages of synergistic species interactions.

The term "IMTA" was coined in 2004 by Jack Taylor, merging the concepts of integrated and multi-trophic aquaculture. Since then, a limited number of countries have adopted IMTA at near-commercial levels, including Canada, Ireland, South Africa, China, Chile, the United States, and the United Kingdom (primarily Scotland).

Additionally, several other countries, such as Portugal, France, and Spain, have conducted significant research to expand IMTA practices. Norway has also made individual efforts in this area, despite having a well-established aquaculture sector.

THE POTENTIAL, ADVANTAGES, AND LIMITATIONS OF IMTA IN SOUTHERN AFRICA

Aquaculture in the Southern African region has seen significant growth, now surpassing traditional capture fisheries in production. However, the aquaculture industryfaces several challenges. Environmental issues, such as overfishing and habitat degradation, pose risks to sustainability. Additionally, technological limitations and inadequate infrastructure restrict access to modern practices. Regulatory inconsistencies further complicate the development of the sector.

Despite these challenges, there is potential for growth through innovative practices like IMTA, which promotes ecological balance and resource efficiency. With increasing global demand for fish, investment in sustainable aquaculture practices and infrastructure upgrades is crucial for the future success of the industry in the SADC region.

Application of IMTA has significant potential in Southern Africa, a region characterized by diverse ecosystems and varying water availability. Below are examples of integrated aquaculture systems tailored to specific countries within the region, where environmental and socio-economic conditions make them particularly suitable.

In countries such as Mozambique, Zambia, Malawi, and Zimbabwe, integrating tilapia (Oreochromis spp) and duckweed (Lemna minor) is beneficial due to the countries' extensive freshwater resources. Tilapia farming produces nutrient-rich water that promotes duckweed growth, serving as high-protein feed for fish and livestock. Adding watercress (Nasturtium officinale) to the combination, can further enhance nutrition for local communities.

Zambia and Zimbabwe would benefit from integrating Nile perch (Lates niloticus) and common carp (Cyprinus carpio) in its freshwater systems, supported by the Zambezi River and Lake Kariba.

The waste from Nile perch promotes plankton growth, which feeds the carp, enhancing productivity for small-scale farmers.

In Namibia, where brackish water aquaculture is ideal, a combination of African catfish (Clariasgariepinus) and freshwater prawns (Macrobrachiumrosenbergii) would be the best fit. This integration recycles nutrients, improving water quality, and efficiently utilizes the limited freshwater resources in coastal and northern regions.In South Africa, estuaries support tilapia (Oreochromis spp.) and oysters (Crassostrea gigas or Ostrea edulis).

The tilapia effluent nurtures oyster growth, while oysters filter the water, aligning with sustainable aquaculture practices and market demands.

These are just a few examples of IMTA species combinations applicable to the region. Let us now examine the potential benefits that can be derived from this innovative practice. IMTA presents a transformative approach for sustainable aquaculture in Southern Africa, particularly in regions like Zimbabwe.

By recycling nutrients from one species as feed for another, IMTA enhances resource efficiency, minimizing the need for external feed inputs and reducing overall production costs. This system effectively addresses waste management issues associated with traditional aquaculture by utilizing filter feeders and detritivores, which leads to improved water quality and lower environmental impact. Additionally, IMTA promotes biodiversity and ecological resilience, increasing the system's ability to withstand diseases and environmental fluctuations, aligning well with the region's emphasis on sustainable practices.

Economically, IMTA empowers aquaculture farmers by diversifying their production and income streams, providing stability against market volatility. The cultivation of multiple species not only creates opportunities for higher financial returns but also enables farmers to generate premium prices through eco-labelling and organic certifications. This holistic approach not only supports local economic development but also fosters community resilience, crucial for Southern Africa's aquaculture sector in the face of climate change and resource constraints.

Overall, IMTA is a vital strategy for promoting sustainable practices while enhancing the profitability and ecological health of aquaculture in the region.

CONCLUSION

Integrated Multi-Trophic Aquaculture (IMTA) is an innovative approach that addresses significant challenges faced by the aquaculture sector in Southern Africa while aligning with global sustainability goals. By promoting a symbiotic relationship among various aquatic species, IMTA improves resource efficiency, reduces environmental impacts, and enhances biodiversity. The potential for IMTA in Southern Africa is substantial due to the region's rich ecosystems and the urgent need for sustainable food production methods. As Southern Africa grapples with overfishing, habitat degradation, and increasing food demands, adopting IMTA can significantly transform the aquaculture landscape. This approach empowers local communities, boosts economic resilience, and paves the way for a more sustainable and equitable food system.

To fully realize the benefits of IMTA, it is essential to integrate innovative practices and invest in necessary infrastructure.

In conclusion, the successful implementation of IMTA in Southern Africa not only offers improved aquaculture practices but also serves as a crucial step toward achieving food security, enhancing livelihoods, and preserving the region's natural resources for future generations. Moving forward, collaboration among stakeholders—including governments, researchers, and local communities—will be vital to harnessing the full potential of IMTA and ensuring a prosperous future for aquaculture in the region.

FACTORS INFLUENCING THE GROWTH OF VANNAMEI SHRIMP (LITOPENAEUS VANNAMEI)

By: Ulises Jaime Lopez Paz

The vannamei shrimp (Litopenaeus vannamei) has positioned itself as a highly relevant crustacean species in global aquaculture, which has stimulated an extensive body of scientific research focused on understanding and optimizing its growth under culture conditions.

SCIENTIFIC STUDIES ON THE GROWTH OF VANNAMEI SHRIMP

The scientific literature specializing in aquaculture offers numerous studies that approach vannamei shrimp growth from a variety of perspectives. Here are a few relevant examples:

* Evaluation of growth and survival of white shrimp (Litopenaeus vannamei) cultured at different salinities and seed densities (MQRInrecherche, 2020): This research analyzed the impact of salinity and seed density on the growth and survival of vannamei shrimp, revealing that seed density exerts a significant influence on growth, the latter being inversely proportional to density.

* Growth of juvenile Litopenaeus vannamei shrimp in two feeding systems (University Review 2018): this study compared the growth of juvenile vannamei shrimp fed two different diets: a commercial diet combined with molasses and a commercial diet mixed with semoline. The results indicate that the molasses-enriched diet promoted higher shrimp growth.

* Comparison of Litopenaeus vannamei shrimp growth under two cropping conditions (CORE, 2017): this research contrasted the growth of vannamei shrimp grown under two different cropping systems: direct seeding and phased seeding. It was noted that the phased seeding system was associated with higher shrimp growth.

FACTORS MODULATING VANNAMEI SHRIMP GROWTH

Vannamei shrimp growth is a multifactorial phenomenon influenced by genetic, environmental and handling elements. The most relevant factors include :

* **Genetics:** the genotype of the shrimp used in culture can have a substantial impact on their growth rate.

* **Nutrition:** complete and balanced nutrition is fundamental for optimal growth of vannamei shrimp.

* **Temperature:** water temperature is a critical environmental factor that regulates growth. The ideal temperature for vannamei shrimp is generally between 28 and 33 degrees Celsius.

* **Salinity:** water salinity also influences growth. Optimum salinity for vannamei shrimp is generally between 15 and 30 parts per thousand (ppt).

* **Seeding density:** the population density of shrimp in a culture pond can affect their growth. Lower densities generally result in higher individual growth.

* **Water quality:** water quality, covering parameters such as dissolved oxygen, pH and nitrogen compound concentration, is essential to shrimp growth and health.

MANAGEMENT STRATEGIES TO OPTIMIZE VANNAMEI SHRIMP GROWTH

Aquaculturists can implement various management strategies to stimulate and optimize vannamei shrimp growth in their cultures:

* **Selecting drives of high genetic quality:** use drives with desirable genetic traits, such as fast growth and disease resistance.

* **Supply of balanced diets:** Formulate and supply balanced diets to meet the specific nutritional requirements of vannamei shrimp at each stage of their life cycle.

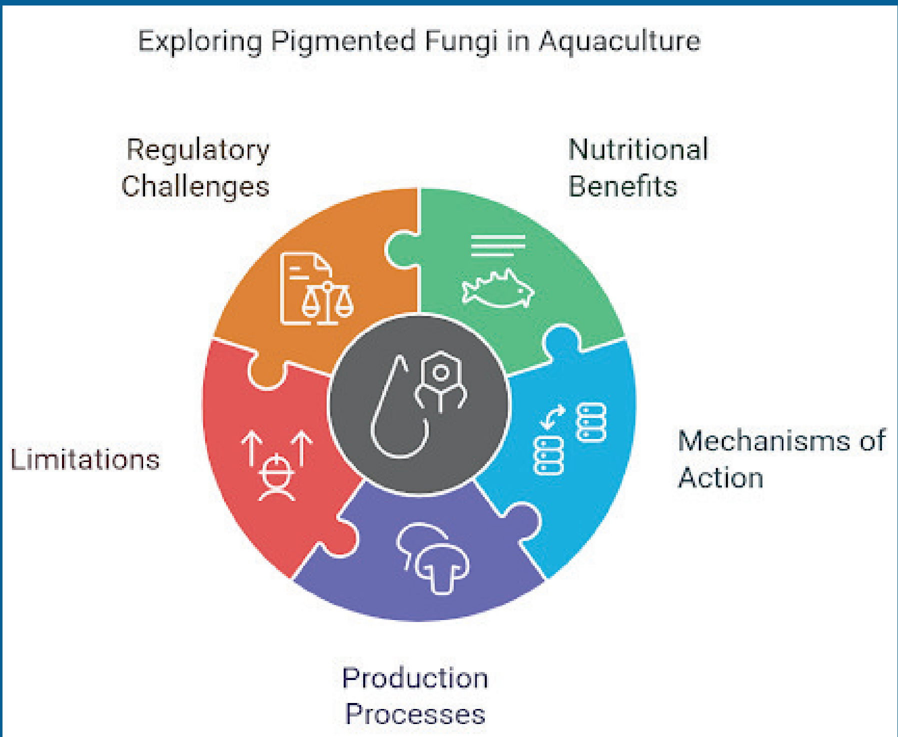
* **Temperature and salinity control:** Monitor and maintain water temperature and salinity within optimal ranges for vannamei shrimp growth.

* **Seed density management:** establish adequate seed densities that promote optimal growth and prevent overcrowding.

* **Water quality monitoring:** implement a regular water quality monitoring program to ensure that water quality remains within tolerable limits for vannamei shrimp cultivation.

By adopting and implementing these management strategies, fish farmers can improve the productive efficiency of their vannamei shrimp crops and achieve more favorable economic results.

USE OF PIGMENTED FUNGI AS ADDITIVES IN AQUACULTURE



The aquaculture industry is facing increasing pressure to adopt sustainable practices that ensure its long-term viability while minimizing environmental impacts.

This document explores the potential of pigmented fungi as nutritional additives in aquaculture, highlighting their benefits for fish health, growth, and pigmentation. It reviews existing research on the application of pigmented yeasts and fungi, discusses their mechanisms of action, and identifies gaps in knowledge that require further investigation. The document also addresses the production processes, potential limitations, and regulatory challenges associated with the use of these innovative additives in aquafeeds.

INTRODUCTION

Aquaculture is one of the most important and rapidly growing sectors of animal production worldwide. Consequently, as the demand for fish and seafood continues to rise, it will trigger a corresponding increase in demand for fish feeds. Nevertheless, due to its high cost and limited availability, fishmeal is no longer the preferred protein source in aquafeeds (FAO 2021). In the last few years, efforts have been made to replace traditional marinederived ingredients in aquafeeds, with more sustainable alternatives. The use of sustainable raw materials in feeds is essential for the successful transformation of aquaculture into a more environmentally friendly sector and for making it easier to adopt the principles of circular economy (Van Doan et al. 2020).

With the increase in intensive aquaculture, fish rearing tends to be even more susceptible to diseases (Chauhan and Singh 2019). Moreover, intensively reared fish are more often exposed to a plethora of stressors that can negatively affect the production by causing conditions such as immunosuppression, reduced growth, loss of appetite, and imbalance of the intestinal microbiota (Gonçalves et al. 2020). Apart from disease resistance, aquacultureprofessionals are always aiming to find ways to improve feed utilization and digestibility. Additionally, they aim to improve organoleptic characteristics such as coloration to meet consumer demands (Dawood and Koshio 2020; Van Doan et al. 2020).

Functional additives may be an efficient way to deal with some of the aforementioned issues (Torrecillas et al. 2018) since typically they are used to increase productivity and enhance the immunity of the farmed fish while causing a lower environmental impact.
Yeasts and fungi belong to this category of additives and although they are still not fully exploited, they are considered one of the newer ingredients emerging in Europe. These ingredients have the potential to transform the food and feed systems and help the transition towards a more sustainable future (EITFood 2022).
Pigment-producing microorganisms are particularly interesting since they possess attributes that can help deal with various production issues. Several fungi and yeasts are known to serve as producers of a variety of natural pigments such as carotenoids, melanins, azaphilones, flavins, phenazines, monascins, violacein, and indigo (Dufossé 2018). The most commonly used microbial pigments available in the global market are monascal pigments, pigments from Haematococcus pluvialis, or Arpink red™ from Penicillium oxalicum (Aman Mohammadi et al. 2022). Fungal carotenoids of commercial value, in particular, astaxanthin could be promising for the aquaculture industry. For instance, they could be used to improve red pigmentation, which is important, not only in salmon farming but also for the rearing of red sea bream, trout, and even for crayfish, lobster, and shrimp (Lim et al. 2018; Weber et al. 2007).
High yields of microbial pigments can be also produced by using a variety of carbon–nitrogen-rich natural substrates like corncob hydrolysate, bakery waste hydrolysates, or peels of inedible fruit matter (Ramesh et al. 2022).
Moreover, the increasing demand for natural pigments like β-carotene, lutein, and astaxanthin highlights the growing niche market for premium healthy natural derived food and feed ingredients (Dufossé 2018). Apart from improving the marketability of the products, natural pigments like these, exhibit antioxidant and antimicrobial properties (Paillié-Jiménez et al. 2020; Tuli et al. 2015). Hence, they could benefit aquatic organisms by stimulating the immune system, increasing stress resistance, and promoting growth and maturation (Pereira da Costa and Campos Miranda-Filho 2020). They also offer sustainable and environmentally friendly solutions for providing essential nutrients, enhancing fish growth, and improving feed digestibility (Gokulakrishnan et al. 2023).
To our knowledge, the potential of pigmented yeasts and fungi applications in aquaculture has not been fully explored. Apart from Phaffia rhodozyma, which has been thoroughly examined for scientific and commercial purposes, the potential of other fungi and yeast species to produce pigments has not been fully explored. Thus, the present work aims to review and address the current knowledge of pigmented fungi and yeasts use in aquaculture.

CURRENT STATUS OF THE USE OF PIGMENTS IN AQUACULTURE

Fish pigmentation is one of the most essential quality criteria influencing the market value of aquaculture species (Vissio et al. 2021) as colour directly affects consumers' decisions and preferences (Gebhardt et al. 2020). or example, non-optimal fillet pigmentation can affect the economic value of rainbow trout fillets up to 40% (Pulcini et al. 2021).
The aquaculture sector has increasingly recognized the importance of pigments in enhancing the quality of fish products. Pigments not only improve the aesthetic appeal of fish but also contribute to their health and growth.

The current trend is shifting towards natural sources of pigments, such as those derived from microbial organisms, to replace synthetic additives.

CURRENT STATUS OF MICROBIAL PIGMENTS AND THEIR APPLICATIONS IN AQUACULTURE

Microbial pigments, particularly those produced by fungi and yeasts, are gaining attention for their potential applications in aquaculture. The most traditional microbial pigments that can be found in the global market, including also aquaculture, are fungal Monascus pigments, astaxanthin from Paracoccus carotinifaciens and microalgae Haematococcus pluvialis, Arpink red™ from Penicillium oxalicum, riboflavin from the fungus Ashbya gossypii, lycopene and β-carotene from the tropical mold Blakeslea trispora or the microalgae Dunaliella salina, and microalgal phytocyanin from Arthrospira platensis (Aman Mohammadi et al. 2022; Dufossé 2018).

These pigments can serve multiple functions, including acting as natural colorants and providing health benefits to fish.

However, the exploration of various microbial species for aquafeed applications remains limited.

BENEFITS OF FUNGAL PIGMENTS IN AQUACULTURE

Multicellular molds, mushrooms, and unicellular yeasts are well-known for a wide range of primary and secondary metabolites with pigments being one of these metabolites (Chandra et al. 2020). In fish, natural pigments are used in aquafeeds as a tactic to achieve brighter flesh and skin pigmentation (Makri et al. 2021).

Fungal pigments offer several advantages in aquaculture, including antioxidant properties, immune system enhancement, and improved growth performance. These benefits can lead to healthier fish and potentially higher market value.

BIOSYNTHESIS OF FUNGAL PIGMENTS

The synthesis of fungal or yeast pigments, like any other secondary metabolites, predominantly involves the polymerization of primary metabolites by specific enzymes (Keller 2019). Fungal pigmentation is influenced by several factors such as the availability of nutrients, the pH, and the temperature (Tudor et al. 2013).

Usually, they are produced under adverse conditions as a response to environmental stressors, like ultraviolet light, ionizing radiation, oxidizing agents, nutrient deprivation, hypersalinity, and host immunoreactivity (Lin and Xu 2023).

Understanding the biosynthesis pathways of fungal pigments is crucial for optimizing their production. Various environmental factors, such as substrate type and cultivation conditions, can influence pigment synthesis, making it essential to identify optimal conditions for maximum yield.

PRODUCTION OF PIGMENTED FUNGI FOR APPLICATION IN AQUACULTURE NUTRITION

Producing an appropriate amount of microbial yield is a critical step in utilizing pigmented fungi effectively for aquaculture nutrition, as it impacts both the nutritional value and economic feasibility of their use in fish feed.

Selecting the fungal species represents the foundational step in producing pigmented fungi for aquaculture applications (Fig 1).

This selection process necessitates determining the specific biopigment of interest, to ensure the desired pigmentation outcomes in the final product.

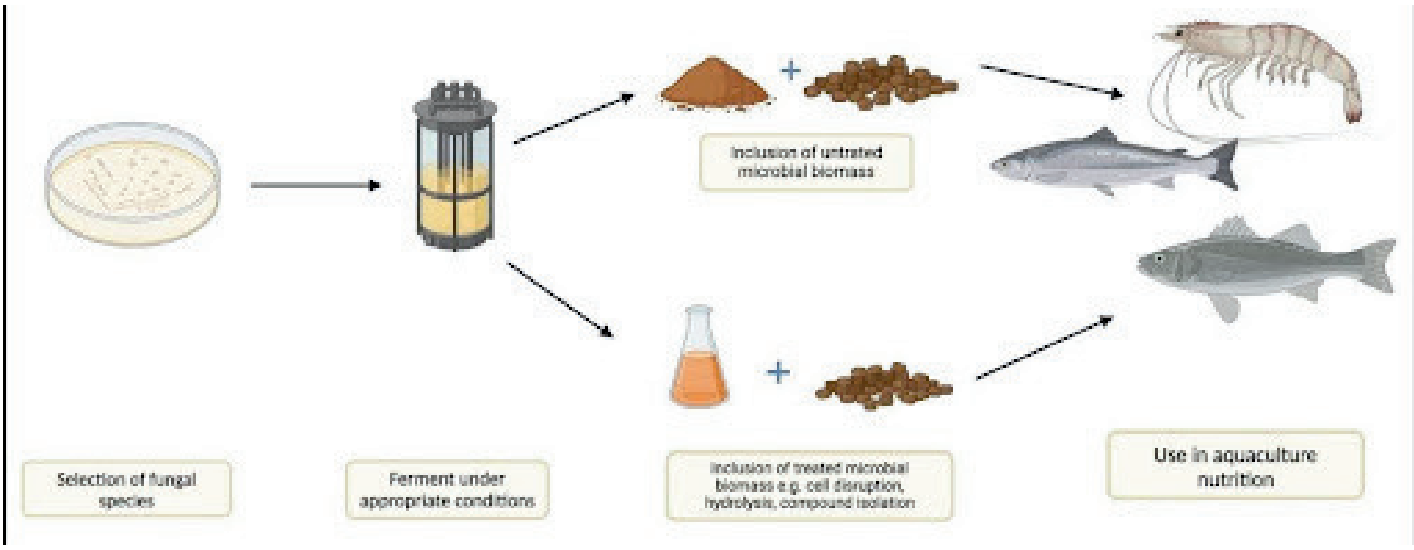


Fig 1: Use of pigmented fungi as additives in aquaculture

The production of pigmented fungi can be scaled up using various substrates, including agricultural by-products. This not only provides a sustainable source of feed additives but also contributes to waste reduction in the agricultural sector.

EFFECTS OF PIGMENTED FUNGI ON FISH GROWTH PARAMETERS

The red yeast Phaffia rhodozyma is an astaxanthin-rich red yeast. Astaxanthin has been shown to increase lipid utilization in fish and therefore to improve growth (Kalinowski et al. 2011). Moreover, fish fed the diets containing the red yeast exhibited better final weight (FW), weight gain (WG), and SGR indices (Kheirabadi et al. 2022).

Research indicates that the inclusion of pigmented fungi in aquafeeds can positively influence fish growth rates and feed conversion efficiency. These effects are attributed to the nutritional value and bioactive compounds present in the fungi.

EFFECTS OF PIGMENTED FUNGI ON FISH LIPID METABOLISM

Adipocytes play an important role in carotenoid storage and are known to have a role in the regulation of genes involved in lipid metabolism (Elvira-Torales et al. 2019; Iqbal et al. 2021). Dietary carotenoids have been found to decrease total lipids, both in the fish flesh and the liver. Moreover, carotenoid supplementation has been shown to decrease the levels of palmitic acid in the whole and liver, a saturated fatty acid known for increasing low-density lipoprotein (LDL) cholesterol, while increasing essential fatty acids like EPA (eicosapentaenoic acid) and DHA (docosahexaenoic acid) in the liver (Nogueira et al. 2021).

Supplementation of synthetic astaxanthin significantly lowered lipid percentages and improved lipid utilization of Pagrus pagrus (Elbahnaswy and Elshopakey 2023).

Pigmented fungi may also play a role in regulating lipid metabolism in fish, potentially leading to improved fat deposition and overall health. Further studies are needed to elucidate the specific mechanisms involved.

EFFECTS OF PIGMENTED FUNGI ON FISH PIGMENTATION

It is well known that fish completely rely on their diet to obtain carotenoids since they are incapable of synthesizing them de novo (Gouveia et al. 2002). The possible use of natural or organic pigments in aquaculture is a topic that requires further investigation (Pereira da Costa and Campos Miranda-Filho 2020). Fungal pigments could serve as an alternative source for an easier and cheaper production of natural pigments (Lagashetti et al. 2019).

The incorporation of pigmented fungi can enhance the coloration of fish, which is a critical factor for market acceptance.

The pigments can contribute to the aesthetic quality of fish products, making them more appealing to consumers.

EFFECTS OF PIGMENTED FUNGI ON FISH BIOCHEMICAL PARAMETERS AND ANTIOXIDANT ACTIVITY

Many microbial pigments such as astaxanthin, granadaene, canthaxanthin, lycopene, riboflavin, β-carotene, and torularhodin can act as antioxidants, stimulating the defense mechanisms against oxidative damage (Sen et al. 2019). Pigmented fungi have been shown to improve various biochemical parameters in fish, including antioxidant activity. This can enhance the fish's ability to cope with oxidative stress, ultimately leading to better health and productivity.

EFFECTS OF PIGMENTED FUNGI ON FISH IMMUNOLOGICAL PARAMETERS

Fungal pigments could also serve as antimicrobial agents against pathogenic diseases. The pigments of R. glutinis have been shown to have an antibacterial effect mainly on gram-positive bacteria and less on gram-negative ones (Yolmeh and Khomeiri 2017). Carotenoid-producing strains of R. mucilaginosa have also exhibited antimicrobial activity against the bacteria Salmonella, Escherichia coli, Staphylococcus aureus, and Listeria monocytogenes as well as the fungi Aspergillus flavus, Aspergillus parasiticus, Aspergillus carbonarius, and Aspergillus ochraceus (Moreira et al. 2018). In this sense, fungal pigments could be considered as new ingredients that not only serve as coloring, but also act as medicine (Narsing Rao et al. 2017). Studies have linked dietary pigments to the stimulation of the immune system and the reduction of serious diseases such as cancer (Maoka 2020). Pigments such as β-carotene, astaxanthin, and lycopene have also been shown to be beneficial for the overall health and immunity of fish (Alishahi et al. 2015; Dawood et al. 2020, 2018).

In addition, pigmented yeasts and fungi could be considered more beneficial in aquaculture, due to the fact that they not only have a rich content of carotenoids, but also because they contain β-glucans, which play an important role as immunity enhancers.

The immunological benefits of pigmented fungi are significant, as they can enhance the fish's immune response and resistance to diseases. This is particularly important in aquaculture, where disease outbreaks can have devastating effects on stock.

EFFECTS OF PIGMENTED FUNGI ON FISH REPRODUCTIVE CAPABILITY

In addition to their aforementioned properties, carotenoids can have an impact on the reproductive mechanisms of fish. Aquatic animals accumulate carotenoids in their gonads (Rashidian et al. 2021). For instance, astaxanthin's most significant application is its use in salmon and trout diets to achieve pigmentation, growth, and reproduction (Schmidt et al. 2011). High levels of astaxanthin are present in salmonoid eggs, enhancing their quality during the initial growth stages and protecting them from UV oxidative injuries (Nakano and Wiegertjes 2020). There have been indications that microbial additives can increase the reproductive performance in captivity-bred species (Hoseinifar et al. 2023).

Research on the effects of pigmented fungi on fish reproduction is still limited. However, preliminary findings suggest that these additives may positively influence reproductive performance, which is crucial for sustainable aquaculture practices.

POSSIBLE LIMITATION HAZARDS LINKED TO THE USE OF PIGMENT-PRODUCING FUNGI

It is known that microbes, in general, can produce toxins or cause diseases. For this reason, fungal and yeast ingredients, as all microbial additives, require extensive screening before their application in aquaculture in order to ensure their safety (Afroz Toma et al. 2023; Gonçalves et al. 2018). For additives such as fungal ones, a user's safety assessment is also necessary to identify potential health hazards related to their use (Bampidis et al. 2023).

Despite the potential benefits, there are limitations and hazards associated with the use of pigmented fungi in aquaculture.

These include the possibility of pro-oxidant effects at high dosages and the need for thorough safety assessments before commercialization.

CONCLUSION

The increasing demand for aquaculture products necessitates the development of high-quality feeds that meet the physiological needs of aquatic organisms. While synthetic additives have been widely used, there is a growing interest in dietary bioactive compounds, including pigmented fungi. These natural additives offer numerous benefits, including enhanced growth, pigmentation, and health of fish. However, further research is essential to fully understand their effects, optimize production processes, and address regulatory challenges.

Balancing the advantages and disadvantages of pigmented fungi will be crucial for their successful integration into aquaculture practices.

Source : Zantioti, C., Dimitroglou, A., Mountzouris, K.C. et al. Use of pigmented fungi as additives in aquaculture. Aquacult Int 33, 162 (2025). https://doi.org/10.1007/s10499-025-01840-0

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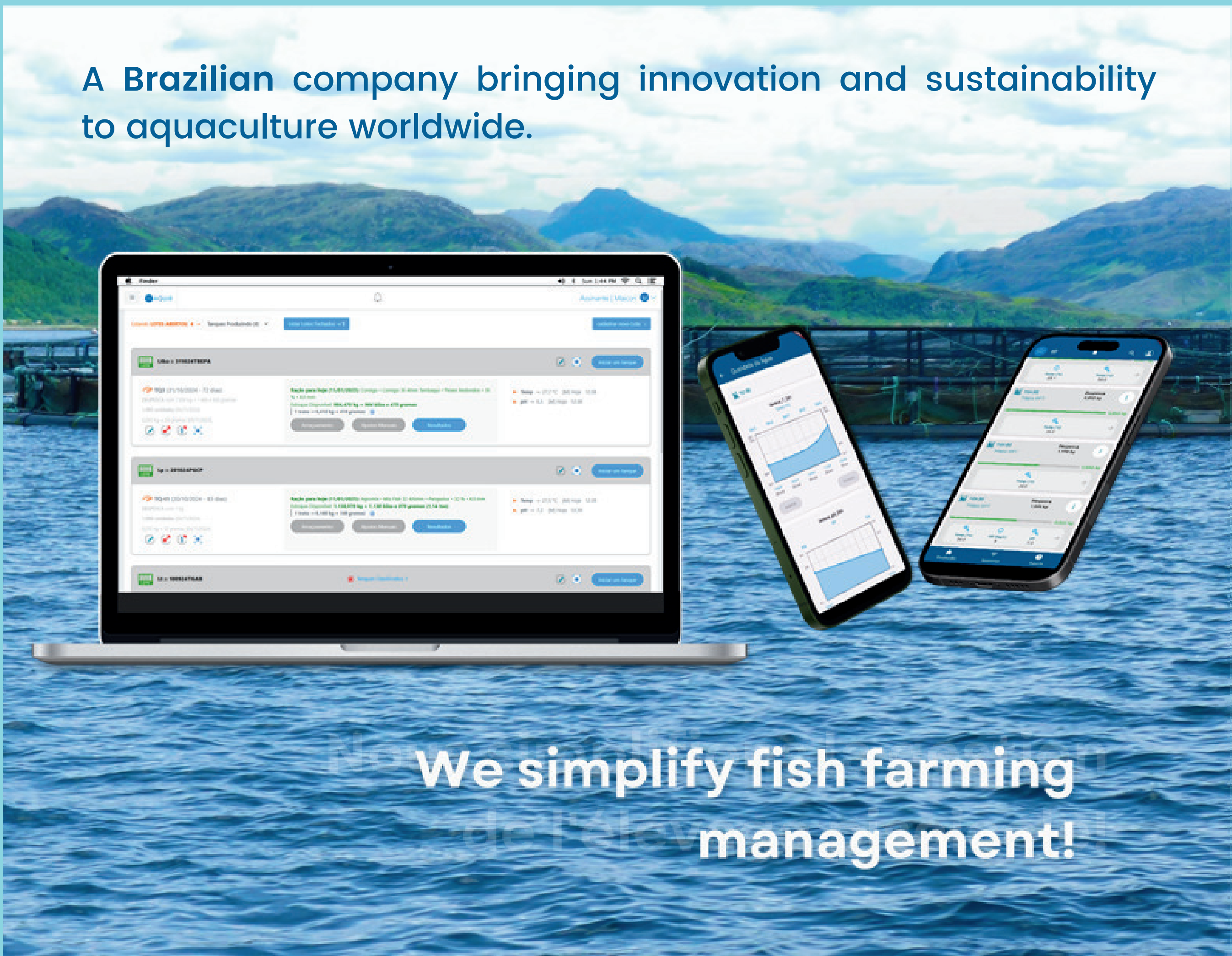

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We simplify fish farming management!

What does **AQUi9** do

AQUi9 provides innovative solutions for **fish farms**, combining **technology** with expertise in production **management**. We develop smart tools to optimize operations, recommend **feeding strategies**, and **monitor feed inventory**, empowering decision-making with accurate data.

Our mission is to make **fish farming** more **efficient** and **sustainable**, ensuring that producers have essential information at their fingertips. We prioritize the responsible use of water resources and the adoption of sustainable practices for a more responsible future in aquaculture.

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AQUi9

Problem We Solve

- **Inefficient Feed Management:** We reduce feed waste and improve feed conversion.
- **Compromised Water Quality:** We ensure a healthier and safer environment for your fish.
- **High Costs:** We lower production costs and maximize profitability.

Solutions We Provide

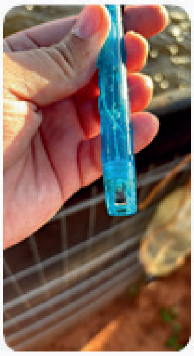
- **Smart System:** Continuous and precise monitoring for real-time strategic decisions
- **Intelligent Feed Management:** Reduced feed waste and higher productivity with sustainability
- **Real-Time Data:** Accurate information for fast, efficient, and traceable decision-making

AQUi9

Smart Monitoring System for Sustainable Fish Farming

Monitor your fish farm's water quality with cutting-edge technology!

IoT Sensors



- Real-Time Water MonitoringinTanks.
- Alerts for anomalies andremote technical guidance.

Monitored Parameters:

- Water Temperature
- Dissolved Oxygen(DO)
- pH

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Smart Monitoring System for Sustainable Fish Farming

Manage your fish farm at your fingertips!

Field App

- Field Ap.
- Schedule feeding management right from your phone.

Never lose your data — access your full history in just a few clicks!

Smart Monitoring System for Sustainable Fish Farming

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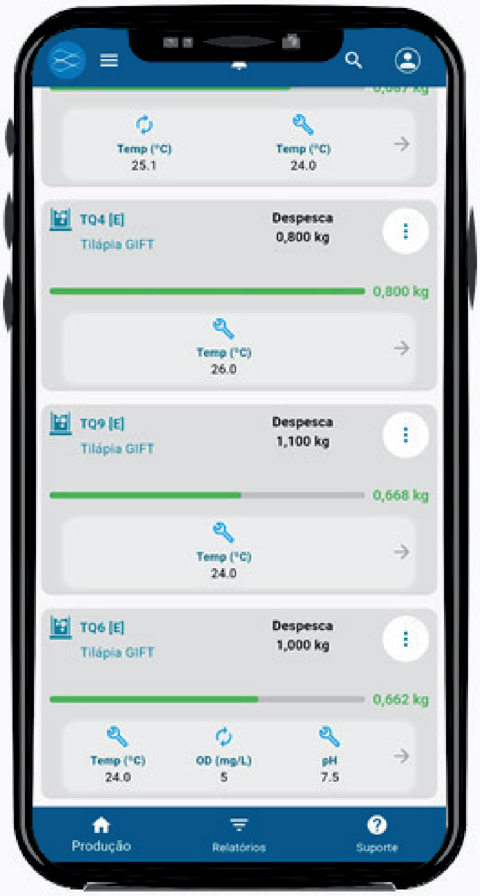
Manage your fish farm at your fingertips!

Field App



- ManageYour ProductionTankby Tank.
- Overseefishgrading andharvest schedules.

Quickly record biometrics and feeding data.

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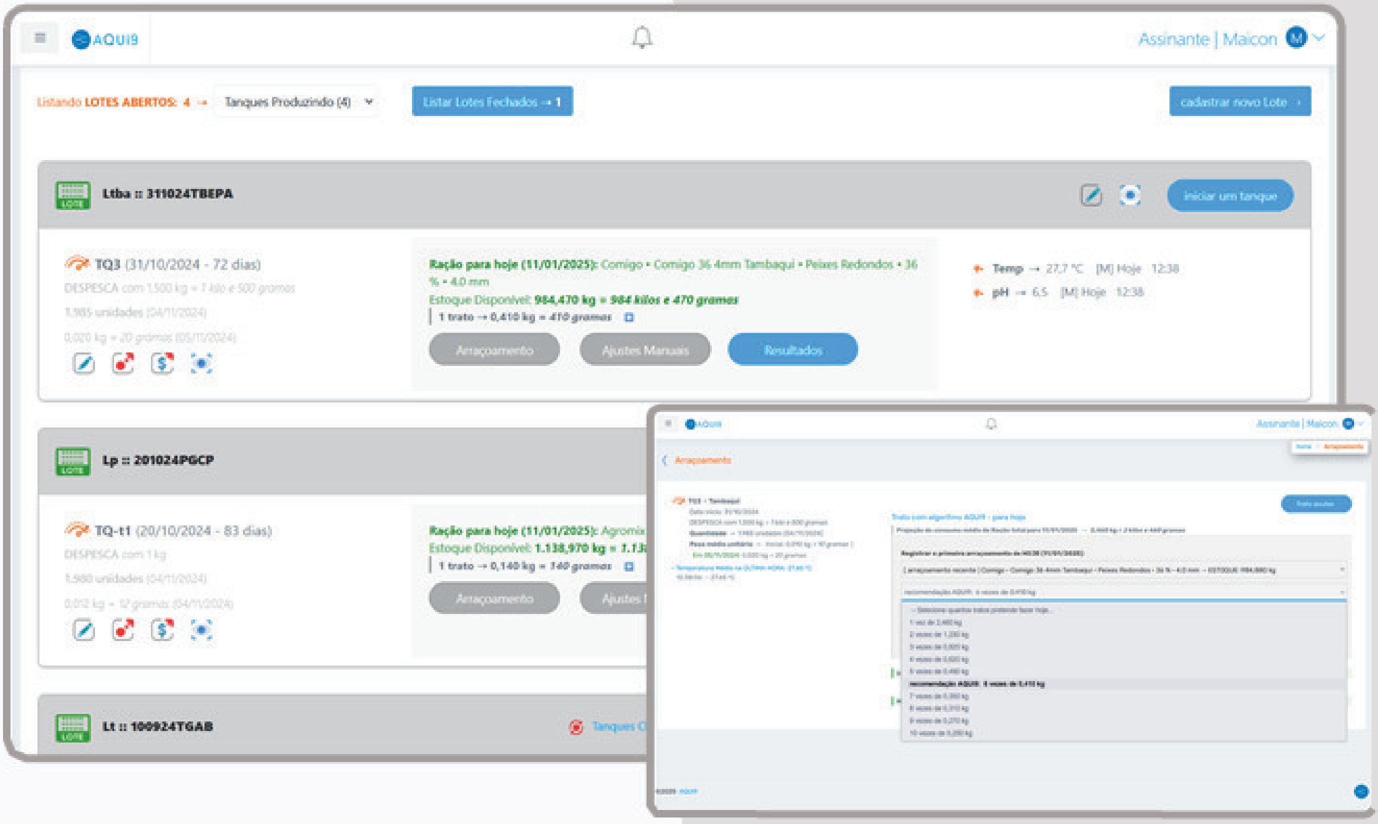
AQUi9

Smart Monitoring System for Sustainable Fish Farming

Field App

Manage your fish farm at your fingertips!



- Tank management at your fingertip.
- Accurate feed stock control

Integrate your tank management history in real-time(sensors,app,and software).

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Smart Management System for Sustainable Fish Farming

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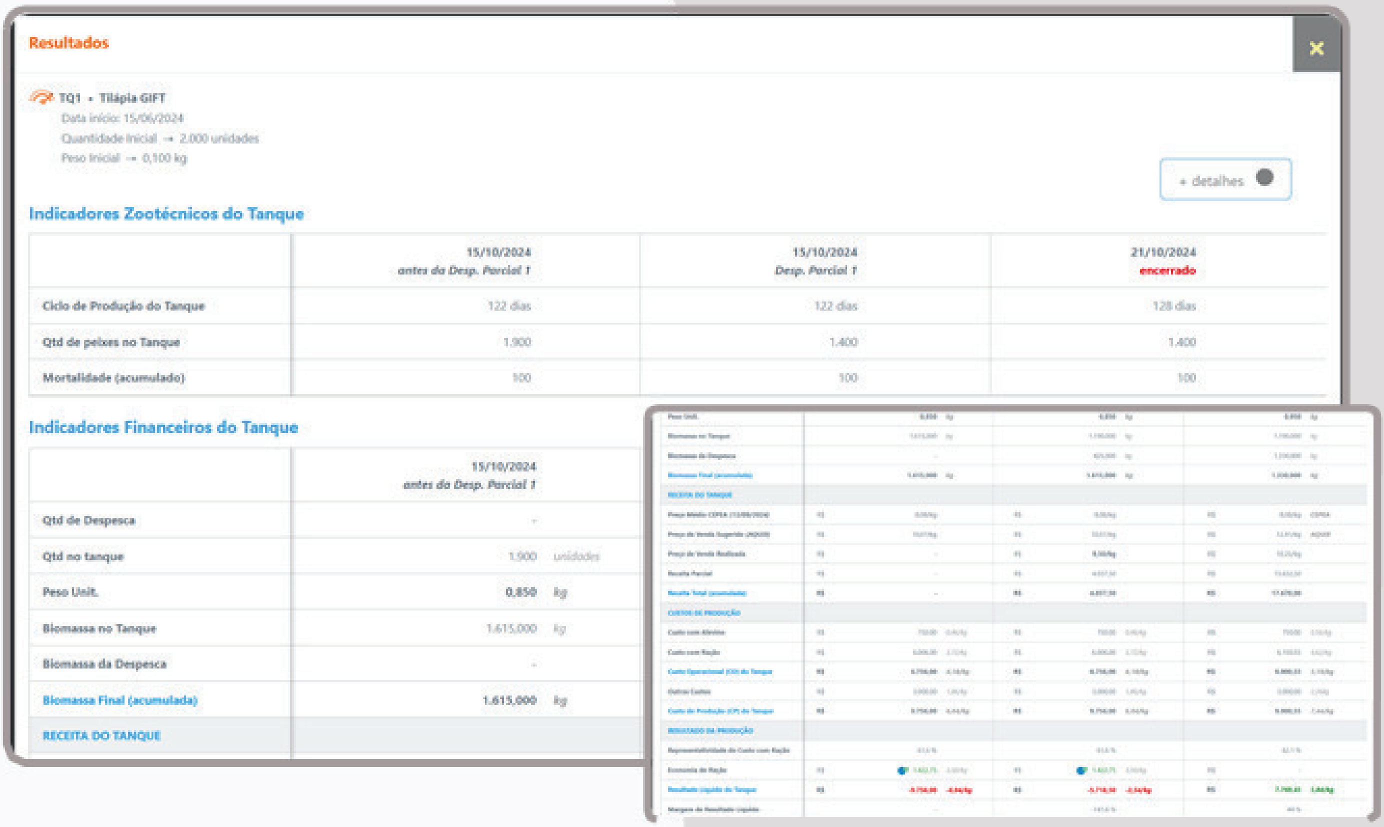
Manage your fish farming operations with just a few clicks!



- Dynamic reports one ach tank's production.
- Simulate your productivity results.

Centralize your production history in one place, ensuring greater transparency and trace ability.

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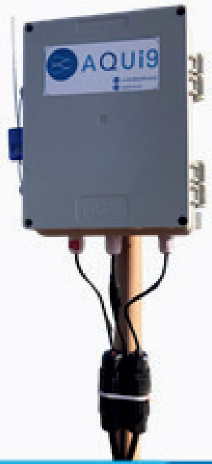
SUCCESS CASE

Efficiency and sustainability in tilapia production in the countryside of São Paulo, Brazil!

"Using AQUi9's system has greatly helped us in the daily management of our fish farm.We have reduced feed waste and improved water quality. The fish are growing healthier every day."
–Giovanna

- (30days)-Reduction in the tilapia production cycle.
- (25%) - Improved feed efficiency witha1.2feed conversion ratio(FCR).
- (20%)-Feed savings and lower production costs (R$ 1.20/kg).

NOSTARIFS



IoTSensors

Starting at

US$ 385

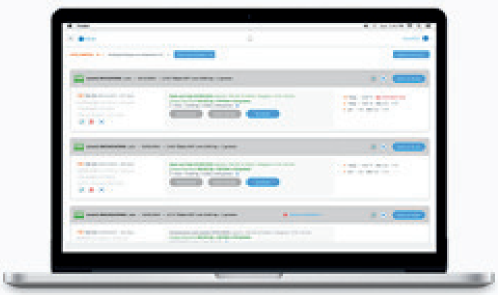
Per device
(check monitored parameters)

App

Starting at

US$ 9,50

Per month
(check premium features)



Software

Starting at

US$ 55

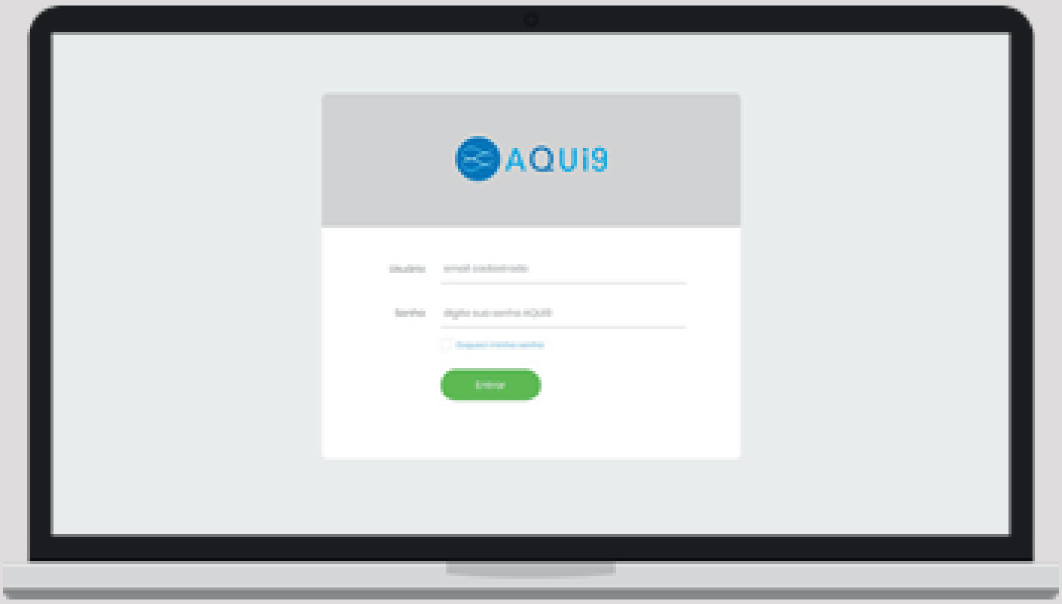
Per month-**START plan**
(production of 1 to 3 tons/month)

The future of **fish farming** is **digital**, **efficient**, and **sustainable**!

AQUi9 is already **transforming** the industry with **Innovation** and **technology**!

JOIN US TO TRANSFORM YOUR FISH FARMING AND TAKE IT TO THE NEXT LEVEL!

AQUi9



A **Brazilian** company bringing innovation and sustainability to aquaculture worldwide.

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NEWS

LIVING LAB OPEN DAYS AT VICINAQUA, KISUMU, KENYA TO SHOWCASE THE FUTURE OF AGRICULTURE AND AQUACULTURE

Vicinaqua site, Kisumu, Kenya, showcased the future of agriculture and aquaculture at the Living Lab Open Days on February 21, 2025. Organized by the Kisumumu County Government and PrAEctiCe, the event united government officials, researchers, organizations, financial institutions, and community members, including delegations from Kilifi County.

The demonstrations showcased a variety of agroecological equipment, efficient irrigation systems, and innovative smart farming tools designed to enhance agricultural productivity.

As ABL (Aquaculture Barn Limited), we showcased our expertise in what we've done before in raised ponds construction, RAS systems construction, and fingerling and fish production, noting our successful youth empowerment program and plans to expand. The event emphasized youth empowerment, technology integration, and public-private partnerships.

Mr. Kenneth Onyango, CEC Member for Agriculture, Fisheries, and Livestock Development, reaffirmed the County's support for youth in agriculture and technology adoption. The Open Days underscored the potential of agriculture and aquaculture to boost economic growth, create jobs, and enhance food security.

IN MALAWI, MINISTER OF NATURAL RESOURCES AND CLIMATE CHANGE, DR. OWEN CHOMANIKA VISITS KASINTHULA AQUACULTURE CENTRE

In Malawi, the Department of Fisheries has the honour of hosting the Honourable Minister for Natural Resources and Climate Change, Dr. Owen Chomanika, on his familiarisation visit to selected institutions and facilities in the southern region of Malawi.
On 28th January 2025, the Minister visited key sites, including: Mangochi District Council (Fisheries Office); Malawi College of Fisheries; Namiyasi Monitoring, Control, and Surveillance construction site and Domasi Aquaculture Centre.
These visits aim to assess ongoing activities in the field.

During his engagements, the Minister is holding discussions with departmental staff, addressing challenges, and outlining the way forward for the sector.

They also provide strategic guidance to support improvements in fisheries management and the sustainable development of aquaculture.

Looking ahead, Honourable Dr. Chomanika visited Kasinthula Aquaculture Centre on 31st January 2025, continuing his tour of the Ministry's facilities and project sites across the region.

The Minister is accompanied by the Secretary for Natural Resources and Climate Change and other senior ministry officials, reaffirming the government's commitment to strengthening Malawi's natural resources management and sustainable development.

ILRI AND AU-IBAR STRENGTHEN COLLABORATION WITH NEW MOU ON LIVESTOCK DEVELOPMENT

The International Livestock Research Institute (ILRI) and AU-IBAR have strengthened their long-standing collaboration by signing a Memorandum of Understanding (MoU). This milestone agreement, signed during the WOAH Regional Conference for Africa, reinforces their commitment to advancing livestock development and animal health across the continent.

A STRENGTHENED PARTNERSHIP FOR LIVESTOCK DEVELOPMENT

ILRI, a non-profit international research institute co-hosted by Kenya and Ethiopia, is at the forefront of livestock research to improve food security and alleviate poverty in Africa and Asia. AU-IBAR, a specialised technical agency of the African Union Commission (AUC), is crucial in coordinating the sustainable use of animal resources among AU Member States. The newly signed MoU strengthens the alliance between these two significant stakeholders in livestock and animal health, paving the way for more structured and effective collaboration.

Speaking during the signing, AU-IBAR's Director, Dr. Huyam Sahil, and ILRI's Dr. Fabian Kausche (Deputy Director General – Research and Innovation, who represented ILRI's Director General) both noted that, over the last decade, ILRI and AU-IBAR have collaborated on various projects, including research, capacity building, livestock master planning, feed assessment, policy and strategy development, animal health and welfare, and One Health approaches.

The MoU builds on these accomplishments by establishing a strategic framework for further collaboration.

KEY AREAS OF COOPERATION

The agreement outlines several priority areas where ILRI and AU-IBAR will work together, including:

1. Conducting joint research and innovation to address difficulties in livestock systems, climate change resilience, feed and fodder production, animal genetics, animal health, veterinary services, and One Health approaches.

2. Improving animal resource governance and management through better data availability and use.

3. Developing and conducting training programs for livestock industry stakeholders to enhance capacity.

4. Assist with policy development and implementation, including support for governance frameworks such National Livestock Master Plans and Biodiversity Strategies and Action Plans.

5. Facilitating technology transfer and scaling up innovations to enhance cattle productivity and health.

6. Foster resource mobilisation and public-private partnerships by collaborating with governments, development partners, and private sector actors to support priority initiatives.

7. Increased awareness and advocacy for animal resource management through knowledge exchange, investment prioritisation, and policy engagement.

ENHANCE REGIONAL COOPERATION, INTEGRATION, AND TRADE FACILITATION:

The collaboration is consistent with important continental frameworks such as the Livestock Development Strategy for Africa (LiDeSA) 2015-2035 and the Animal Health Strategy for Africa 2019-2035. AU-IBAR has been instrumental in the development of these techniques, and ILRI's research-driven approach supplements these efforts by delivering evidence-based solutions for long-term livestock development.

The goals of AU-IBAR are perfectly aligned with ILRI's Corporate Strategy 2024-2030, which focusses on unleashing the potential of sustainable livestock for better livelihoods and a healthier environment. The collaboration will help to shape policies, scale up technologies, and ensure climate-smart, biodiversity-friendly livestock systems that benefit over 300 million people in Africa.

LOOKING AHEAD

The Memorandum of Understanding between ILRI and AU-IBAR is a forward-thinking move towards increasing continental partnership in livestock and resource development. By exploiting each other's strengths, both institutions want to hasten the transformation of Africa's livestock sector, assuring food security, economic growth, and resilience to impending threats such as climate change and zoonotic disease.

This agreement lays the groundwork for future collaborative activities and demonstrates ILRI and AU-IBAR's commitment to driving effective research, policy development, and innovation for the benefit of Africa's livestock-reliant populations.

STRATEGIC AQUACULTURE TRANSFORMATION PROGRAM IN COTE D'IVOIRE TARGETS TRAINING OF 3,000 YOUNG AQUAPRENEURS

The General Coordinator of the Strategic Program for Aquaculture Transformation in Côte d'Ivoire (PSTACI), Mr Modibo SAMAKE, met with two delegations from the Tchologo and Gbêkê regions on Thursday February 6, 2025.

The aim of this joint mission, which took place at the Koubi fish farm in Tiébissou, was to thoroughly assess the progress made in the technical training of the 49 learners coming from various regions, to evaluate the effectiveness of the methods being taught, to visit the aquaculture facilities, and to closely follow the young trainees in their day-to-day activities and practical sessions. The mission also aimed to address the important issue of post-training support.

This initiative represents a valuable opportunity for youth from all regions of the country to access high-level diploma training in aquaculture, while contributing significantly to improving food security in Côte d'Ivoire.

The project aims to train 3,000 young people from all regions of Côte d'Ivoire, bearing in mind that the Programme Stratégique de Transformation de l'Aquaculture en Côte d'Ivoire (PSTACI) aims to create a viable, structured and developed aquaculture sector in Côte d'Ivoire.

INAUGURATION OF A FISH FARM AT MERINA NDAKHAR IN SENEGAL

Eiffage Opérations Services (EOS), in partnership with the Agence Nationale de l'Aquaculture Senegal (ANA), inaugurated a fish farm at Mérina Ndakhar in Senegal on Monday, February 17, 2025, an initiative dedicated to aquaculture in order to generate a positive impact for local populations by launching this ambitious sustainable development project.

With this in mind, EOS, with the support of the ANA, is assisting local populations by providing resources, appropriate training and a management structure to encourage the growth of this activity.

Aquaculture, a sector mainly developed in developing countries, plays a key role in food security and the fight against poverty.

This project will enable producers to increase their income while developing new skills.

At the launch ceremony, Dr Samba Kâ, Managing Director of Senegal's ANA, and other officials attended the stocking of ponds and the start of theoretical training.

Source : ANA Sénégal.

AFRICA NEEDS INNOVATIVE POLICIES TO MEET FUTURE DEMANDS IN THE AQUACULTURE SECTOR

According to the report Policy Innovations for Sustainable Fisheries and Aquaculture in Africa A Malabo Montpellier Panel Report 2025 of agriculture and food security experts highlights, the rapid growth of the continent's fisheries and aquaculture sector, which, since 2000, has experienced the highest aquaculture growth rate of all regions of the world, increasing by more than five-fold to reach 2.5 million metric tons (MT) in 2022. The sector provides almost 20 per cent of Africa's animal protein.

To counter a projected deficit of 11 million MT annually by 2030, policies and investments are needed to meet future demand and avoid potential shortages, the authors argue.

Africa's supplies of aquatic foods would need to increase by 74 per cent by 2050 to maintain current per capita fish consumption levels.

Africa boasts a vast network of both marine and inland freshwater fisheries. Production in both capture fisheries and aquaculture has been expanding in recent years—in aquaculture, Africa now has the highest growth rate globally. The fisheries and aquaculture sector's growth has improved food security and nutrition, created jobs, and enhanced economic development across the continent.

There is an opportunity to expand the sector further, given the increasing demand for fish in Africa due to rising population growth, increased urbanization, and higher incomes in many African countries. Overcoming the growing deficit in fish production relative to demand may be achieved by addressing challenges within the sector related to overfishing, pollution, climate change, and resource depletion.

Moreover, the rising demand for sustainably farmed fish presents expanded opportunities for fish farmers but will require greater promotion of aquaculture across the continent. Transparency and environmental stewardship in fish production can help fishers and fish farmers tap into premium, niche markets for organic or eco-friendly fish products, increasing their profits and improving their economic resilience by expanding the range of markets they supply. Several African governments have developed comprehensive policy frameworks to address the challenges slowing the development of their fisheries and aquaculture sectors. However, such efforts need to be expanded and intensified to strengthen fisheries and aquaculture value chains, transform Africa's aquatic food systems, and contribute to broad economic growth.

Transforming Africa's fisheries and aquaculture sector requires collaborative efforts from all stakeholders, including governments, researchers, development partners, the private sector, and local communities.

This report Policy Innovations for Sustainable Fisheries and Aquaculture in Africa provides an overview of government actions that have contributed to creating a conducive environment for the sustainable development of the continent's fisheries and aquaculture sector.

The report specifically draws on the experiences of four African countries—**Ghana, Malawi, Morocco, and Mozambique**—to showcase policy and institutional innovations and programmatic interventions that may be replicated and scaled up in other countries.

The Action Agenda presented by the Malabo Montpellier Panel draws on the experiences of the four countries to highlight several key factors underlying their success.

INFRASTRUCTURE, TECHNOLOGY, AND REGULATIONS INVESTMENT:

To foster growth in both aquaculture and capture fisheries, African governments need to prioritize investment in infrastructure such as hatcheries, preservation, and processing facilities — especially those that utilize renewable energy to reduce operational costs, and investments in innovative technologies that support nutritional, economic, and environmental goals. This includes exploring systems such as integrated multi-trophic aquaculture (such as rice-fish farming).

Moreover, mobile technologies are essential in filling data gaps, improving resource management, and streamlining communication between farmers, researchers, and regulators. A robust monitoring and enforcement framework is necessary to tackle illegal, unreported, and unregulated fishing. This can be achieved through investments in tracking systems and the enforcement of legal penalties.

STRENGTHEN SUPPORT FOR SMALLHOLDER AQUACULTURE:

Governments and development partners need to develop financial products that cater specifically to the needs of smallholder fish farmers, such as microloans, low-interest credit, and insurance options. Mobile apps could also provide f ish producers with vital market information, helping them secure better prices and reduce postharvest losses by improving efficiency across the supply chain.

Technical training and skills development programs are also critical to help small-scale farmers adopt modern, sustainable practices that improve their productivity while minimizing environmental impacts. Furthermore, national and regional policies need to facilitate market linkages, increase access to inputs, and integrate fish farmers into the broader fish value chain.

SUPPORTING INNOVATION AND INCREASE RESEARCH FUNDING:

To build a skilled workforce capable of driving innovation in the sector, it is crucial to establish innovation hubs and mentorship programs that are inclusive of youth and women, focused on boosting sustainable fish production and promoting improved fish processing, marketing, and trade.

Additionally, more resources need to be directed toward research on sustainable fisheries and aquaculture to address the funding gap. Improving data collection on fish stocks and consumption trends will help policymakers make more informed decisions for productivity enhancement.

Efforts to mobilize these funds involve active participation in international policy and negotiating dialogues. Offering tax incentives to fisheries and aquaculture research institutions and strengthening collaboration between governments, the private sector, and universities can help leverage resources and expertise in research focused on the fisheries and aquaculture value chains.

ENHANCE REGIONAL COOPERATION, INTEGRATION, AND TRADE FACILITATION:

Existing frameworks like the African Union's Policy Framework and Reform Strategy for Fisheries and Aquaculture offer a foundation for collaboration. Regional efforts need to focus on harmonizing fishing regulations, such as standardized gear, quotas, seasons, and conservation measures, to prevent overfishing, reduce illegal, unreported, and unregulated fishing, and protect marine biodiversity.

Additionally, establishing common certification and labeling systems would improve trade by ensuring that fish products are sustainably sourced and of high quality. Streamlining customs procedures and eliminating tariffs will promote easier movement of fish and fish products across borders, benefiting both producers and consumers.

By strengthening regional cooperation, Africa can share best practices, build capacity, and create more efficient, sustainable fisheries and aquaculture systems.

EVENTS

AQUACULTURE EUROPE 2025, VALENCIA, SPAIN IN SEPTEMBER 22-25

Aquaculture Europe 2025 will take place in Valencia, Spain in September 22-25. The theme is "**Aquaculture for everyone.**"
With its diversity of species and production technologies, its diversity of market propositions and with its reverence for the environment and the way in which this is changing, Aquaculture is established as an essential sector in global food supply.

The event will cover the full scope of European aquaculture scientific disciplines and species and will comprise submitted oral and poster presentations. AE2025 will also feature an international trade exhibition, industry forum, student sessions and activities, satellite workshops and updates on EU research.

IN CAMEROON, IN DOUALA, 4 IN 1 FISH FARMING TRAINING AT MENDEL CENTER WITH AWARD OF CERTIFICATES

Mendel center organizes a training in fish farming with certification:
- Theoretical and practical training in fish farming
- from March 28 to 30, 2025
- At the practical fish farming center MENDEL CENTER located in Douala kp 12 Baobab entrance.

During this training, we will give you the following skills
1- Skills for the production of Catfish fish with any type of water
2- Skills for the production of tilapia and carp in above-ground tanks *by renewing its water once a week
3- Skills on the detection and treatment of sick fish
4- Skills on how to set up your fish farming project from A to Z

Reserve your place quickly at 698010453 / 674026399 mendelcentercameroun@gmail.com

For the training session which goes from March 28 to 30, 2025.
Training time: 8 a.m. - 1 p.m.
Number for deposit: 698010453/674026399
NW: only 15 places are available

AQUAFUTURE SPAIN THE INTERNATIONAL AQUACULTURE INDUSTRY EXHIBITION, FROM 20 TO 22 MAY 2025

The International Aquaculture Industry Fair, Aquafuture Spain, is the largest technological, educational, informative and commercial event in the aquaculture sector in southern Europe. Will take place from 20 to 22 May 2025 at the IFEVI – VIGO exhibition centre.

Aquafuture Spain represents the entire aquaculture sector: from marine and continental aquaculture with all its variety of fish, through to the cultivation of molluscs (mussels, oysters, clams, etc.) and tackling new challenges such as algae cultivation.

Visitors and exhibitors will be able to enjoy the different spaces offered by Aquafuture Spain in order to address all the current and future challenges of the sector, both technological and commercial.

THE WORLD AQUACULTURE SAFARI 2025, WILL TAKE PLACE FROM 24-27 JUNE 2025 IN SPEKE RESORT MUNYONYO, ENTEBBE, UGANDA

WORLD AQUACULTURE SAFARI 2025: Biggest Aquaculture Meeting in Africa will be held at Speke Resort Munyonyo, Kampala, Uganda (near Entebbe) with involvement from countries throughout Africa and the world.

East Africa is the fastest growth node for aquaculture on the African continent. This is predominantly as a result of the farming of tilapia, but several other species contribute to the sector. East Africa is also a world leading region in the farming of seaweed, with exciting developments around several other marine species such as sea cucumber and more. The EU-funded TRUEFISH Project, which seeks the advancement of aquaculture in the Lake Victoria Basin was a major sponsor of the meeting.

Through Egypt (2022), Zambia (2023) and Tunisia (2024), the African Regional Aquaculture (AFRAQ) Conferences have shown steady growth.

It is, however, important to emphasize that Aquaculture Safari 2025 is not just any ordinary event — it is a prestigious World Aquaculture Conference, integrating both the continental gathering and a high-profile global showcase event that brings together key stakeholders from around the world.

Undoubtedly, it will address key African topics such as tilapia and catfish production, but the conference will cater to a global audience covering a diverse range of presentations, species, meetings, discussions, workshops and more.

The trade show and exhibition promises to assemble the largest selection of aquaculture goods and service providers under one roof, in Africa, to date.